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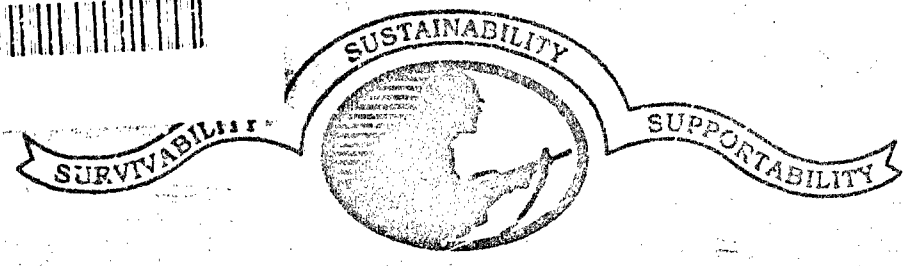

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LIGHTWEIGHT PASSIVE MICROCLIMATE COOLING DEVICE

by
Clyde F. Parrish
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Mainstream Engineering Corporation
Rockledge, FL 32955

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August 1991 - March 1992

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The intermittent adsorption cooling concept has been successfully demonstrated and has produced cooling rates in the 300 W range. The design requirement of 300 W for 6 hours has not been demonstrated due to system leaks. However, we demonstrated in laboratory experiments that were scaled to a much smaller size that we have produced 325 to 432 W of cooling. Laboratory experiments also showed the system could operate for more than 8 hours, be started and stopped, when the system contained no leaks.

The current prototype was constructed of brass and copper for ease of fabrication. No consideration was given to weight. We have examined alternate methods of construction of the backpack and cylinder assembly and thin (0.01 in.) stainless steel could be used. The stainless steel sheet stock could be formed into a backpack bending the sheets into fins, which also serve to strengthen the backpack. Also, stainless steel could be used to lower the weight of the cylinders. With these changes, the system weight, including water and desiccant, is 23.8 lb.

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PREFACE

This Final Report was prepared by the Chemical Systems Division of Mainstream Engineering Corporation in Rockledge, Florida. The report, prepared under contract number DAAK60-91-C-0104, is being submitted to the U.S. Army Natick Research, Development and Engineering Center.

This report summaries work done between August 13, 1991 and March 9, 1992.

Heidi Danziger of the Individual Protection Directorate was Project Officer for this report.

EXECUTIVE SUMMARY

We have successfully demonstrated that it is possible to produce cooling rates in the range of 300 W with an intermittent adsorption cooling concept. These systems can provide, when properly constructed, the design requirement of 300 W for 6 h. We have been able to produce 180 W for 10 to 20 min even though we were not able to eliminate leaks in the system. However, we demonstrated in laboratory experiments that were scaled to a much smaller size, that we should have produced 325 to 432 W of cooling. Laboratory experiments also showed the system could operate for more than 8 h, be started and stopped, when the system contained no leaks.

The current prototype was constructed of brass and copper for ease of fabrication. No consideration was given to weight. We have examined alternate methods of construction of the backpack and cylinder assembly. Stainless steel currently appears to be the metal of choice. When thin (0.010 in.) stainless steel sheet stock was examined, it was found that a backpack could be formed by bending the sheets into fins, which also served to strengthen the backpack. The cylinder assembly could be constructed of either smooth wall or baffled tubing. With these changes, the weight of the backpack could be lowered to 6.1 lb and probably even lower if the support of the desiccant was considered in the calculations. The tube assembly weight could be lowered to 3 lb. These changes would provide a system weight including water and desiccant of 23.8 lb.

LIGHTWEIGHT PASSIVE MICROCLIMATE COOLING DEVICE

INTRODUCTION

IDENTIFICATION AND SIGNIFICANCE OF THE PROBLEM

Mainstream Engineering has been working for several years on the development of personal cooling systems. Traditionally, the passive approach has been to use a phase-change material that "melts" and adsorbs body heat. Although this approach works quite well, the weight penalty becomes prohibitive for cooling times greater than 1 h and is therefore unacceptable for a 6-hour chemical warfare cooling application. Alternatively, an active refrigeration system could be used in which a fuel is used to power an active air conditioning system. For this type of active refrigeration system, the best design appears to be a vapor-compression-type system in which the fuel is combusted in an engine which provides shaft work, which in turn drives a compact vapor-compression air conditioning system, thereby providing the cooling. Such a design is superior to Stirling or Brayton approaches in terms of efficiency and weight. However, today's technology for the internal combustion power source dictates an approximate engine mass of 3 lb, which consumes approximately 6 lb of fuel during the 6-hour cooling period. Therefore the desired 15-pound weight requirement is already burdened with 9-pounds of engine/fuel weight, making the overall 15-pound requirement difficult unless engine/fuel efficiency improvements are mastered. Multifuel operation also remains to be addressed.

Because the cooling requirement is not continuous, but instead is only needed for 6 h (because of protective capacity time constraints), the intermittent-adsorption microclimate cooling systems offer improved mass and reliability features. The design for this contract used a water vest cooling configuration with only one moving part the, thermal control valve. The system was designed to supply up to 300 W of cooling for a period of up to 6 h. After the 6-hour cooling period, the backpack was designed to be removed and recharged. The backpack recharging stand was designed to recharge the adsorption bed by heating it electrically with resistance heaters.

DETAILS OF THE ADSORPTION BACKPACK DESIGN

The adsorption personal cooling device uses only one moving part, a pressure-regulating valve. The operating concept is to evaporate a working fluid from a sealed vest and capture this working fluid in an adsorbent bed that rejects heat to the environment. As discussed in a later section, the rate of adsorption of the working fluid vapor on the bed is very fast, and the pressure-

regulating valve is used to control the vest evaporation to maintain the desired vest operating pressure and thus maintain the desired vest operating temperature for all heat loads.

The wearer's vest is actually the evaporator of the system and the adsorption bed serves as the condenser. Figure 1 presents a block diagram of the system. The vest is initially filled with liquid working fluid, and as the system absorbs heat from the body, this working fluid is vaporized. This vapor is transported from the evaporator section to the adsorbent bed by the pressure difference between the evaporator section and the bed. The pressure-regulating valve maintains the desired pressure in the evaporator, this pressure being determined from the desired temperature in the vest and the saturated pressure-temperature relationship of the particular working fluid. For simplicity and ease of recharge, the working fluid proposed for this application is water, and if the desired temperature was 30 °C (86 °F, which is 4-5 °F below the normal body skin temperature), then the pressure-regulating valve would be set to maintain a pressure of 4.2 kPa (0.6 psia) in the evaporator section.

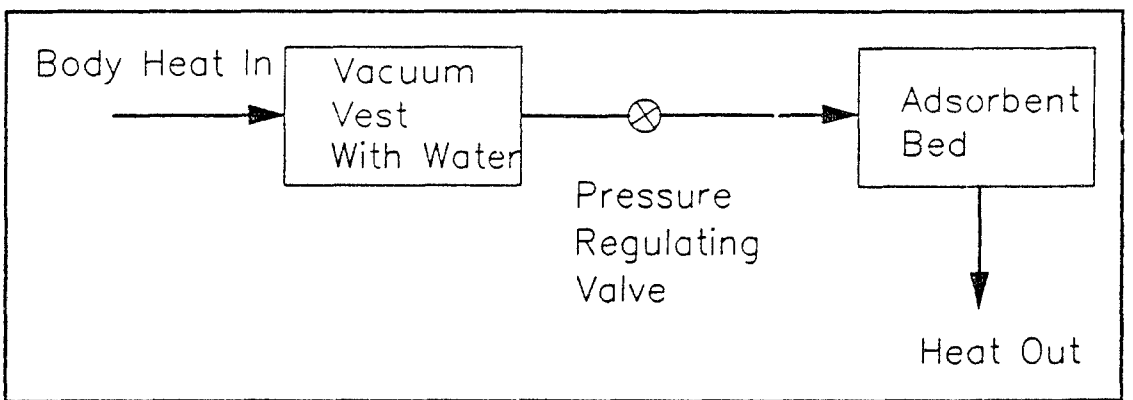


Figure 1. Block diagram of the adsorption system

The adsorbent bed will always maintain a vapor pressure below this pressure as long as the bed is not saturated. This has been confirmed by our experiments, which are presented later. The vest is designed as a parallel passage heat exchanger, so as the working fluid is vaporized, the liquid level drops. The vest contains saturated water (working fluid) with saturated liquid in the lower section and saturated vapor in the upper section, and the liquid level continues to drop until all the liquid has vaporized and the cooling capacity (via evaporation) has been exhausted. The volume of water necessary for the system is determined by the total cooling requirement (cooling rate multiplied by cooling time). For the proposed chemical warfare cooling application, 300 W of cooling for 6 h results in a total cooling requirement of 6,480 kJ, which would

require 2.54 kg (5.58 lb) of water. (The vest is initially filled with water.) The weight of the water equates to a liquid volume requirement of 0.67 gal.

The adsorbent bed of the system is designed to accommodate the total volume of working fluid vapor, which exits the evaporator during operation. The adsorption of working fluid vapor is exothermic, so this chamber will reject heat to the environment and will be finned to promote natural convection cooling. Forced convection will not be necessary. The approximate dimensions of the backpack are 12-inches wide by 12-inches high and 3-inches deep.

A liquid accumulator could be used between the evaporator and the adsorbent bed. This would prevent liquid from entering the bed during transient temporary tilting of the system (for example, when the wearer bends over). Other more sophisticated valves to sense tilting and shut the system off will not be necessary. The liquid accumulator could be placed between the evaporator and the pressure-regulating valve at a high point on the back and plumbed so that the liquid returns to the vest. However, the accumulator has not been included as part of the initial prototype design. Since our bench-top experiments did not indicate any entrainment problems, we believe a single line would operate without problems.

The Recharging System

The adsorption bed is recharged by removing the system from the wearer and placing it on a recharge stand. This stand will consist of a heat source that could be fuel fired (such as a ceramic-wick heater-kerosene heater type), or electrically heated (by resistance heating). Natural circulation will be used to heat the bed and drive the water vapor off the bed. The system is disconnected and recharged separately. The bed would be recharged in the recharge stand and then evacuated, while still hot, with a small hand-operated pump (located on the recharge stand). Bed recharge is very fast because the recharge time is not limited by condensation of the water vapor, which is driven off.

Proof-of-Concept Experiments

Mainstream has performed numerous experiments to demonstrate the feasibility of the concept. The primary concerns were the determination of the best adsorbent material, the recyclability of the selected adsorbent, and the ability of the adsorbent to adsorb the water working fluid fast enough to be used without any active mechanical transport of the working fluid from the vest into the adsorbent bed. These requirements were all successfully demonstrated by the experiments described in this section.

Mainstream is actively involved in the study of physical and chemical adsorption for cooling and water purification. For example, Mainstream is exploring the use of adsorbents for the extraction of water vapor from the atmosphere to provide a source of pure water. Selection of an effective desiccant for water extraction is based on several factors, e.g., extraction rate, water capacity, toxicity, and ease of dehydration. As part of that study, which is illustrated in Figure 2, we examined several desiccants for their rate of water adsorption. In this experiment, we forced air, which contained water vapor, through a desiccant bed and measured the amount of water adsorbed as a function of time. The desiccant with the best rate and capacity was magnesium chloride. Magnesium chloride (molecular weight 95) forms the hexahydrate (molecular weight 203); therefore, 100 g of magnesium chloride will adsorb 113 g of water.

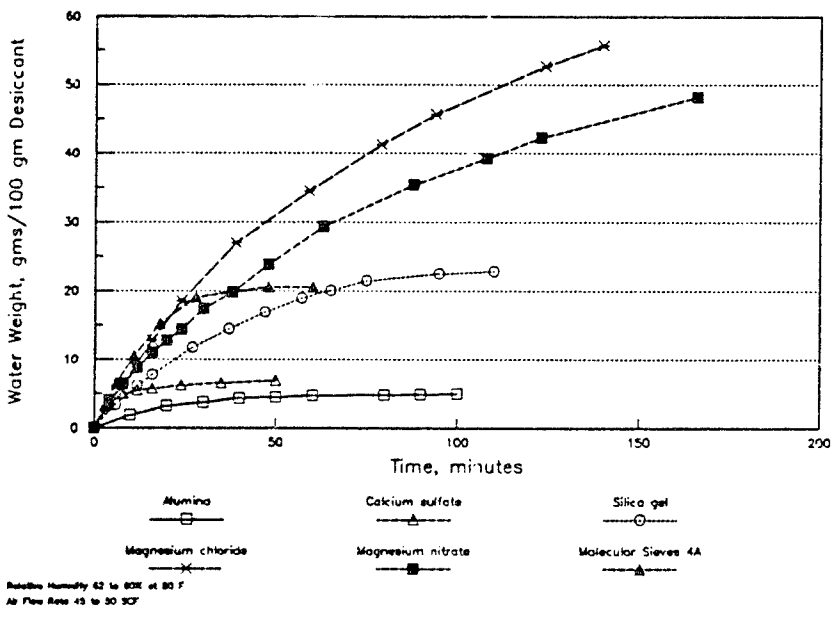


Figure 2. Water extraction from air for various desiccants

In a second experiment, the transport of water vapor from the evaporator (vest) to the adsorbent bed (backpack) was simulated. Water was placed in a vessel (simulating the evaporator vest and the temperature maintained at 35 to 38 °C by the addition of heat), and anhydrous magnesium chloride was placed in a second vessel, which represented an unfinned adsorbent bed. These vessels were connected with tubing (valves were used to isolate the water and desiccant). The system was initially evacuated, and the valves between the water vessel and the desiccant bed were opened. The magnesium chloride weight increase, which was the result of the formation of the hexahydrate, was monitored as a function of time. Figure 3 presents a plot of the time required to form the hexahydrate.

The weight increased above 100%, which is the weight of anhydrous magnesium chloride, since the weight of water adsorbed to form the hexahydrate is greater than the weight of the anhydrous desiccant. For the magnesium hexahydrate to be easily dehydrated without caking, the adsorption should be stopped before all of the hexahydrate is formed. (Assuming the adsorption is stopped at 95% of completion, 100 g of magnesium chloride will be allowed to only absorb 95% of 113 g or 107 g of water). This was assured in the actual backpack cooling application by designing the vest capacity for liquid water to be 107% (by mass) of the adsorbent bed mass.

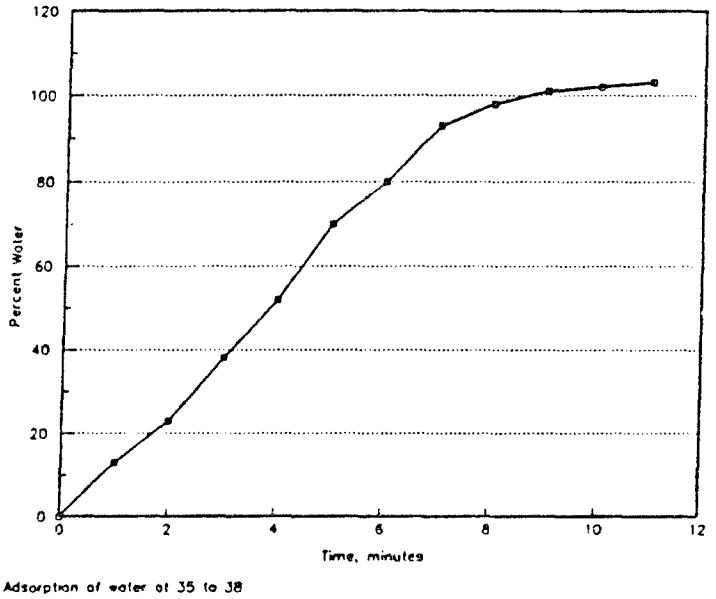


Figure 3. Water adsorption on magnesium chloride

These experiments clearly illustrate that water can be transferred as vapor from the evaporator to the anhydrous magnesium chloride desiccant bed in a short period of time. In the example shown in Figure 3, the magnesium chloride was fully hydrated in 9 min. This rate of diffusion is much faster than that required for the backpack operation where a total of 6 h is available for complete hydration. Also a total of 21.2 g of water was transferred as vapor through approximately 6 inches of 0.18 inch i.d. tubing in 9 min. This represents a linear flow rate of 335 ft/sec. To transfer the 5.81 lb of water that would exist in a full-scale backpack cooling system in the required 6 h time period, the connecting tubing would need to be at least 0.31 inches in diameter.

TECHNICAL OBJECTIVES

The primary objective of this effort is to experimentally demonstrate the feasibility and benefits of the adsorption-backpack cooling design. This effort addresses 1) detailed component level design; 2) construction of the preliminary prototype systems; 3) development of detailed size, weight, reliability, and performance data from the experimental data; and 4) revision of the prototype microclimate cooling systems for U.S. Army applications.

WORK PLAN

INTRODUCTION

The thrust of this effort is to use existing expertise in the mechanical/thermal-design area to demonstrate one of Mainstream's innovative intermittent-adsorption microclimate cooling systems.

PROGRAM TASKS

Task 1. Finalize the Design of the Adsorption Cooling System

Mainstream engineers, with the assistance of the U.S. Army Natick engineers, finalized the implementation of the Mainstream adsorption cooling designs for microclimate control. This specific implementation of the design considered factors such as performance, weight, size, operational and procurement costs, efficiency, RAM, and MANPRINT considerations with emphasis on safety. Preliminary design drawings, along with performance estimates, were prepared and presented at the Task 2 design review. Bench-top experiments were performed as necessary to investigate the feasibility of the various components of the preliminary design. Mainstream addressed all the key requirements including methods of heat transfer, multifuel burner recharge system (when applicable), and prototype system demonstration. Laboratory scale bench tests were performed as necessary to support the design effort.

Task 2. Design Review

Mainstream held a design review at Natick facilities (to ensure the greatest possible attendance of Natick engineers) to discuss the preliminary designs of Mainstream's adsorption microclimate cooling system. Army suggestions and recommendations were incorporated into the design. The results of this meeting were included as part of the monthly report and circulated to all attendees. The report included a summary of the events of the meeting, the actions items developed, and the revisions to the preliminary designs.

Task 3. Prepare the Detailed Construction Drawings

Mainstream prepared detailed manufacture and assembly drawings for the production of the prototype system. These drawings were of sufficient detail to allow a breadboard system consisting of all the major functional components to be built and experimentally tested to demonstrate the feasibility of the proposed Mainstream approach.

Task 4. Demonstrate the Prototype System

The system developed under Tasks 1-3 will be constructed and used to demonstrate the feasibility, efficiency, performance, reliability, and maintainability of the Mainstream concept.

Task 5. Documentation

This task will include the preparation of all technical reports, including bimonthly status reports, data sheets, and presentation materials, as well as any modifications to the manufacturing drawings when needed.

The final report will include technical data, drawings, and instructions (for operation, recharge, and maintenance of both types of systems). Design considerations, tradeoffs, and options will be discussed for the each prototype. The Final Report will also include any lessons learned or recommendations for future developments.

DISCUSSION OF RESULTS

A contract initialization meeting was held at the start of the effort to discuss project requirements with the key personnel involved with the project. This meeting was used to review the staffing and timing needs in order to meet the contract requirements, while meeting the demands of other programs. We also reviewed the contract deliverables and highlight the key steps required to keep the contact on schedule. The agenda for this contract meeting is given below:

August 15, 1991
AGENDA

1. Program Tasks
2. Labor Requirements
3. Major Contract Requirements
4. Design Concepts for Vest and Backpack
5. Testing Requirements
6. Deliverable Items

TASK 1. Finalize the Design of the Adsorption Cooling System

Review of the Literature

The chemical literature was reviewed to determine if other absorbent systems could be used; however, our selection of magnesium chloride or magnesium nitrate appeared to be the best choice. The capacity of molecular sieves or silica gel is too low to meet the design weight requirements.

System Safety Program

A System Safety Program was prepared based on the requirements of MIL-STD-882B. This program includes the system safety, system safety program, system safety program plan, and system hazard analysis. This plan was prepared and submitted within 30 days after the start of the contract, and the final version of the System Safety Program is included as Appendix A. The System Hazardous Analysis Report is included as Appendix C.

Laboratory-Scale Adsorption Measurements

A small laboratory-scale adsorption system was set up to test the desiccants to determine which system would be most effective for this backpack design. This laboratory device can measure the system pressure, reservoir temperature, bed desiccant temperature,

and bed weight. Figure 4 shows a sketch of this design. These measurements were made by immersing the water reservoir in a calorimeter and measuring the temperature change for cooling and immersing the adsorption bed in the calorimeter for heating. The relative rates of adsorption can also be monitored. These data were helpful in determining the best adsorbent material to select.

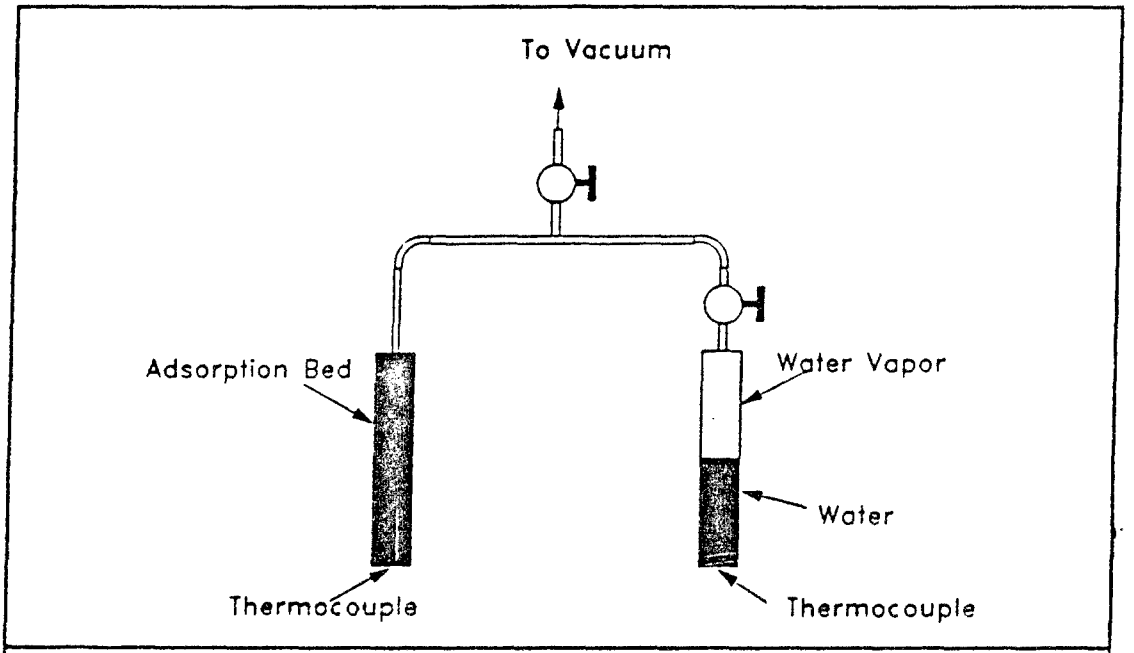


Figure 4. Sketch of the laboratory-scale adsorption cooling system

The results of these measurements are summarized in Tables 1-3 and illustrated in Figures 5-7. In these studies we monitored the temperature of the adsorption bed and the water reservoir as a function of time. The important feature of these studies is the relative rates of heating and cooling. For example, molecular sieves and silica gel rapidly adsorb the water and quickly saturate, while magnesium chloride reacts more slowly. This slower rate of adsorption of magnesium chloride provides the type of cooling desired for the 6-hour application. In one case, magnesium chloride adsorption was followed for over 8 h and the difference between the heating and cooling curves remained constant even when the system was stopped overnight and restarted.

Table 1. Heating and Cooling Rates for Molecular Sieves			
Desiccant	Time (min)	Temp Bed °C	Temp Water °C
Molecular Sieves	0	26	21
	1	25	32
	2	23	40
	3	22	45
	5	18	52
	10	16	58
	20	16	58
	40	11	47
	60	13	41
	90	16	32
	120	20	26

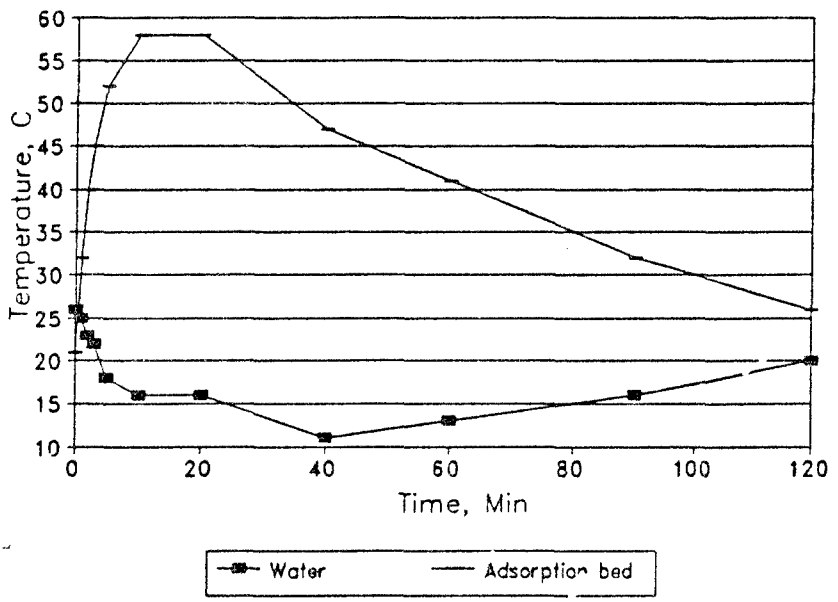


Figure 5. Water adsorption on molecular sieves

Table 2. Heating and Cooling Rates for Silica Gel			
Desiccant	Time (min)	Temp Bed °C	Temp Water °C
Silica Gel	0	23	25
	1	25	32
	2	23	40
	3	22	45
	5	19	52
	10	16	58
	20	13	56
	40	11	47
	60	13	41
	90	16	32
	120	20	26

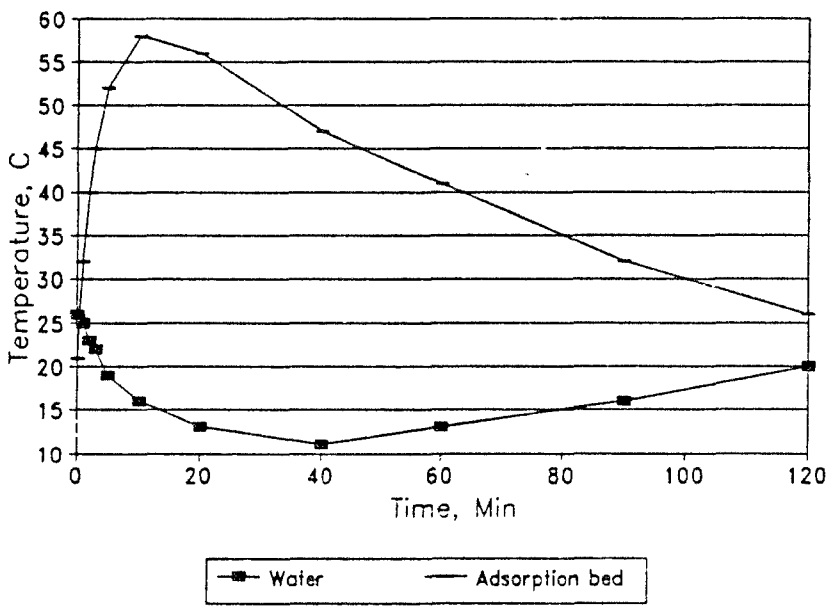


Figure 6. Water adsorption on silica gel

Table 3. Heating and Cooling Rates for Magnesium Chloride			
Desiccant	Time (min)	Temp Bed °C	Temp Water °C
Magnesium Chloride	0	23	25
	1	22	28
	2	22	33
	3	21	36
	5	20	38
	10	17	40
	20	16	38
	40	16	37
	60	15	36
	80	15	36
	100	15	36
	110	15	36
	120	15	36

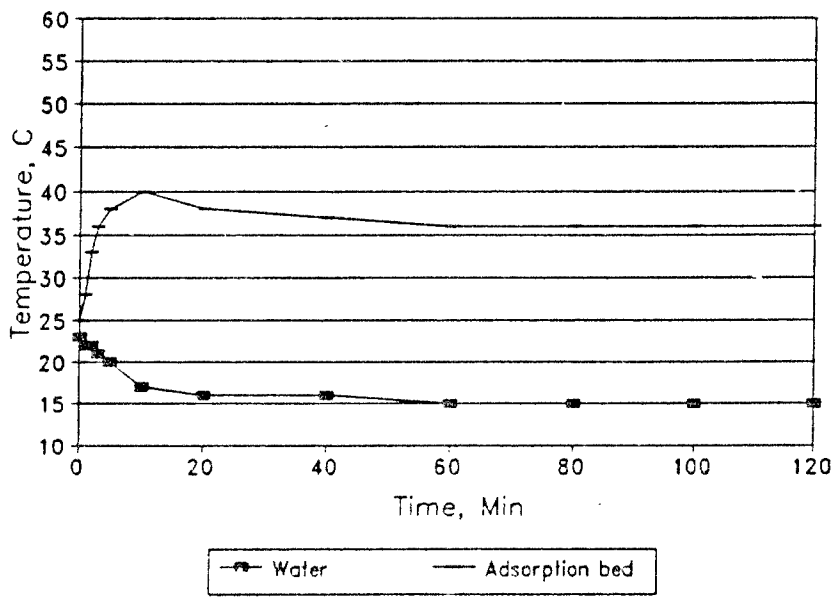


Figure 7. Water adsorption on magnesium chloride

Laboratory Cooling Rates

A number of laboratory experiments were performed to obtain an estimate of the cooling capacity of the fully assembled backpack. Our laboratory setup, shown in Figure 4, was used to obtain this estimate of the cooling capacity. The water reservoir was immersed in one liter of water contained in an insulated vessel. A heater was placed in the vessel and the temperature adjusted to 35 °C to simulate the temperature under conditions when the vest would be worn. Then, the valve between the water reservoir and the backpack was opened to allow the water vapor to flow to the desiccant. As the water reservoir started to cool, the voltage to the heater was increased. After 30 min to 1 h the system stabilized and the change in the voltage before and after cooling started was measured. The resistance of the heater was measured and the increased power requirement was calculated. The results of these experiments are summarized in Table 4. Additional studies were made to improve the rate of cooling. It was found that by adding a small amount (6 to 12 wt% of the magnesium chloride) of molecular sieves 4A, the rate of the adsorption increased. Molecular sieves 4A is a better desiccant for adsorption of water than magnesium chloride. Therefore, by placing the molecular sieves below the magnesium chloride there would be a tendency to cause the water vapor to flow through the magnesium chloride. This increase in the flow through the desiccant appears to have improved the rate of adsorption on magnesium chloride. These results are also shown in Table 4.

Table 4. Summary of Laboratory Cooling Capacity Measurements

Conditions	Cooling Rate
Magnesium Chloride with 12% Molecular Sieves 4A	10.2 W
Magnesium Chloride with 12.2% Molecular Sieves 4A	9.5 W
Magnesium Chloride with 6.8% Molecular Sieves 4A	7.0 W
Magnesium Chloride with 6.8% Molecular Sieves 4A (Recycled Adsorbent Bed)	6.0 W

The decrease in the cooling capacity for the recycled material was probably due to a leak in the adsorption system, since all of the materials used in these experiments were from either oven-dried or vacuum-system-regenerated desiccant.

Full-Scale Backpack System Capacity

The capacity of the backpack system could be controlled by two factors. Either the surface area of the water is limiting the rate of evaporation of the water vapor and controlling the cooling rate, or the surface area of the adsorption bed is controlling the water vapor concentration over the desiccant bed. Therefore, both the

bed surface area and evaporator surface area were estimated and compared with the laboratory system. The areas of the laboratory system's adsorption bed and water reservoir were both 0.785 $in.^2$, since both were constructed from 1-inch i.d. tubing. The area of the full-scale water reservoir is 25.9 $in.^2$; therefore, the cooling capacity would be 325 W (9.85 x 33). The area of the full-scale adsorption bed is 34.4 $in.^2$ (3 inch x 12 inch - 2 x 0.785 $in.^2$); therefore, the cooling capacity would be 432 W. Thus, we should have covered the capacity for either factor.

Mainstream Design Review Meeting

A second design meeting was held to review the options for the vest and backpack design. The drawings of this design were prepared for the review meeting held at Natick November 22, 1991. The basic concerns were to develop a design of the vest that could maintain a vacuum for long periods of time and still provide the wearer comfort and flexibility. We have determined that stainless steel bellows tubing is very flexible and lightweight. Therefore, we have selected this material for the connections between the evaporator and the adsorption bed. We also made calculations to estimate the mechanical strength of the backpack and heat transfer characteristics. The results of these calculations are given below.

Mechanical Strength Calculations

When we calculated the mechanical strength of the brass box to determine the effect of atmospheric pressure, we found that the box was overdesigned by a factor of over 100. This extra strength has been a major factor for the excessive weight of the current design.

Heat Transfer Calculations

Estimates were made of the heat transfer from the backpack to the surroundings. The following assumptions were made:

Air at 1 atm and 325 K,

Film temperature, $T_f = 325K$

Density, $\rho = 1.0877 kg/m^3$

Kinematic viscosity, $\nu = 18.225 x 10^{-6} m^2/s$

Thermal conductivity, $K = 0.02814 W/mK$

Prandtl number, $Pr = 0.725$

Heat flow, $q = 300W$

The surface area of the box is:

$$A = 0.2787 m^2$$

The heat flux, $q'' = 1076.39 W/m^2$

Coefficient of thermal expansion, $\beta = 1/T_f$

The Grashof number:

$$Gr_L^* = \frac{g\beta q'' L^4}{K\nu^2}$$

$$Gr_L^* = 3.0 \times 10^{10}$$

Therefore, the flow is laminar

The Nussett number, $Nu_L = \frac{5}{4}(0.6)(Gr_L^* Pr)^{\frac{1}{5}}$

$$Nu_L = 87.06$$

$$Nu_L = \frac{hL}{K}$$

The heat transfer coefficient, $h = 8.0377 W/m^2 K$

If there is no fin, then

$$q = hA(T_w - T_\infty)$$

$$T_w = 158.9°C$$

For brass, $K_f = 111 W/mK$

The design of the fins for the backpack will be 7/8 in. long and 3/32 in. thick; therefore, $L_c = L + \frac{t}{2}$

$$L_c = 0.0234 m$$

$$Am = tL_c$$

$$Am = 5.5758 \times 10^{-5} m^2$$

For the quantity $L_c^{\frac{3}{2}}\left(\frac{h}{KAm}\right)^{\frac{1}{2}} = 0.129$

The fin efficiency, $\eta = 0.98$.

The maximum allowable tip temperature is 50 °C.

$$m = \left(\frac{hP}{K_c A}\right)^{\frac{1}{2}}$$

$$m = 7.7986$$

$$T_b = 50.4168°C$$

$$q = hA\eta(T_b - T_\infty) = 0.129$$

$$A = 1.498 m^2$$

It is possible to calculate the number of fins. The extra area due to the fin = 1.21975 m^2 and the area of each fin is 0.0135 m^2. Therefore, a total of 90 fins would be required. This would give a spacing of 3 fins per in., which we used in the design.

Based on these calculations, the design with brass as the material of construction should reach the design temperature of a maximum tip temperature of 50 °C. The surface area of the box is 0.2787 m^2. Therefore, we had an increase in the total convection surface area of the box of 5.37.

TASK 2. Design Review

A review of the contract was held at Natick November 22, 1991. We discussed the overall design concepts and the results of the laboratory experiments. However, proof of the cooling concept in a full-scale unit was determined to be the primary objective of the first prototype. Other comments are listed below after the list of attendees.

Scott Bennet, Natick (Army), (508)651-5442

Scott Smith, NCTRF-ESD, (508) 651-4740

Bob Kinney, Natick (Army), (508) 651-4538

Walter Teal, NCTRF-ESD, (508) 651-4740

Rodger Masadi, Natick (Army), (508) 651-5443

Heidi Danziger, Natick (Army), (508) 651-5439

Clyde Parrish, Mainstream Engineering, (407) 631-3550

1. MANPRINT considerations were discussed and it was decided if there was to be any input into the current prototype design then it should be made before December 6, 1991. Two points were discussed; one was the placement of the control valves, and the other was the penetration of the cooling lines through the jacket. We have updated the design based on these discussions and the updated design is presented in a later section. We did not receive any comments; therefore, we made no additional considerations with regard to MANPRINT.

2. It was decided that the prototype could be constructed with copper tubes and the difference in weight would be estimated for the materials that would be recommended for the final product.

3. The best desiccant, to date, is magnesium chloride and a copy of its current MSDS is attached.

4. The cooling rates observed in the laboratory are low; however, it should be possible to correct this problem by increasing the available surface area.

5. The maximum surface temperature for the backpack should be 120 °F (49 °C) based on discussion at the review meeting.

6. It was confirmed that the design cooling rate and capacity was 300 W for 6 h.

TASK 3. Prepare the Detailed Construction Drawings

Heat Loads and Capacities

The current design of the water reservoir has 9 water tubes 1 inch in diameter and 9 inches long and 6 tubes 2 inches in diameter and 9 inches long which would give a total of area of 25.9 $in.^2$ (167 cm^2) and a volume of 233 $in.^3$ (3.82 L). The volume of the current backpack design is 12 inches by 12 inches by 3 inches or 432 $in.^3$ (7.04 L).

The requirement of 300 W of cooling for 6 h corresponds to the absorption of 6480 J. This would then require the evaporation of 2.54 kg of water for the vest. The volume of 2.54 kg of water is 2.54 L, which is within the capacity of the vest manifold of 3.82 L. The excess volume would provide extra vapor capacity and surface area for improved evaporation rate. To adsorb the 2.54 kg of water would require a minimum of 2.54 kg of magnesium chloride/molecular sieve mixture. The bulk density of the magnesium chloride/molecular sieve mixture is 0.535 kg/L; therefore, it would require a bed volume of 4.75 L. The current design has an overall volume of 7.04 L, which is adequate. Part of this volume is not available due to the regeneration tubes and the needed free-board for distribution of the water vapor over the top of the desiccant bed.

Revised Vest and Backpack Design

Preliminary drawings were presented at the November 22, 1991, review meeting. Several suggestions were made as a result of that meeting and modifications were made to facilitate construction. The selected construction drawings are shown in Figures 8-11. A complete set of construction drawings are shown in Appendix B.

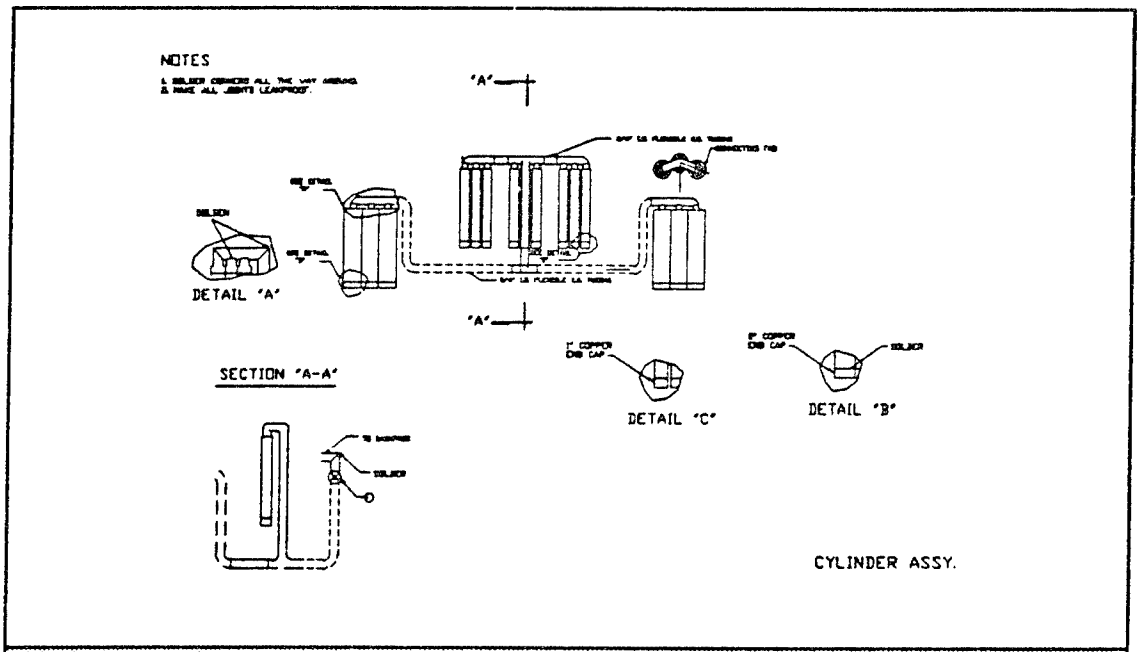


Figure 8. Cylinder assembly

This illustration shows how the cylinders that contain the water are connected. The two groups of three tubes on the left and right sides of the assembly are connected to the center three groups by flexible stainless tubes. This arrangement allows the end groups to wrap around the body of the wearer so that these groups are in the front. The side tubes are 2 inches in diameter and they are arranged in an angle pattern to be more comfortable for the wearer. The valve between the water reservoir and the desiccant bed has been moved to just below the attachment to the backpack. A lightweight flexible stainless tube has been used to make the connections between the three sets of tubes on the wearer's back, between the side bundles, and between the backpack and the reservoir manifold.

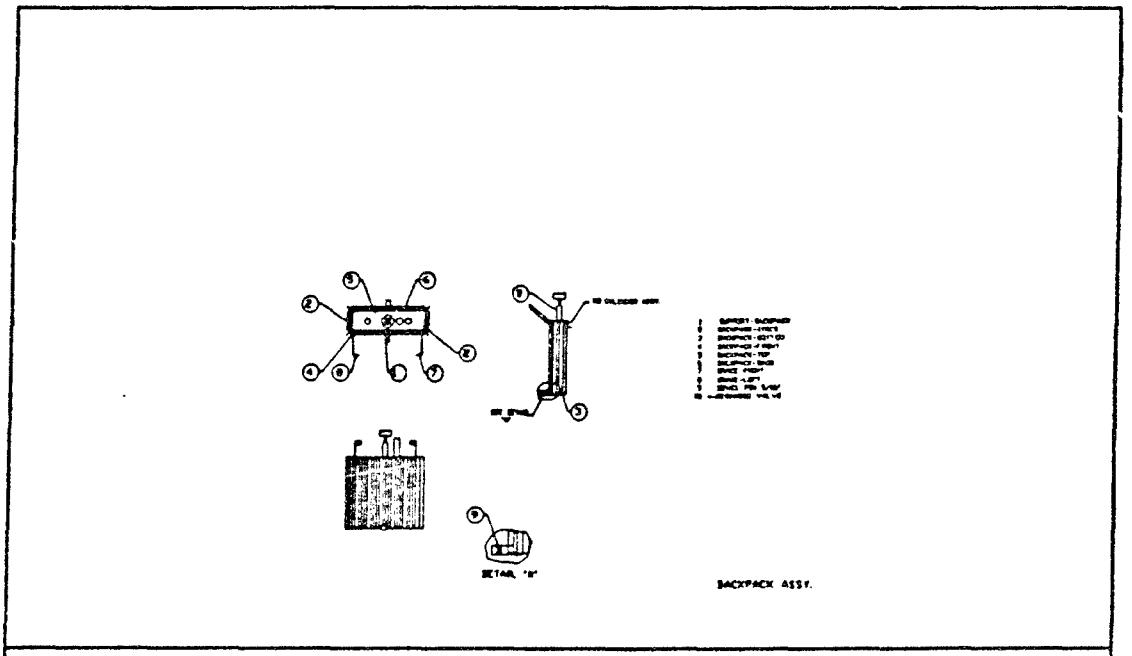


Figure 9. Backpack assembly

The outside of the backpack is illustrated in Figure 8 where the connection to the evaporator tubes, the control valve, and the recharging valve are shown. This view also shows the flexible connection of the backpack to the wearer's back. For the prototype, the backpack was constructed of brass. Two tubes that go through the bed will recharge the desiccant. Safety thermal switches were placed in the tubes above the heaters to control the bed temperature at a maximum of 300 °C while the system is recharging. Fins have been added to the backpack to aid in cooling and to prevent the wearer from touching the hot surfaces. Calculations have established that the maximum surface temperature should be around 50 °C. The backpack attaches to the metal frame and has a stop so that it may be lowered away from the back so that a protective coat may be placed over the vest, but not over the backpack. When the vest is pulled back in position, shoulder straps will be used to support the backpack in the normal upright position.

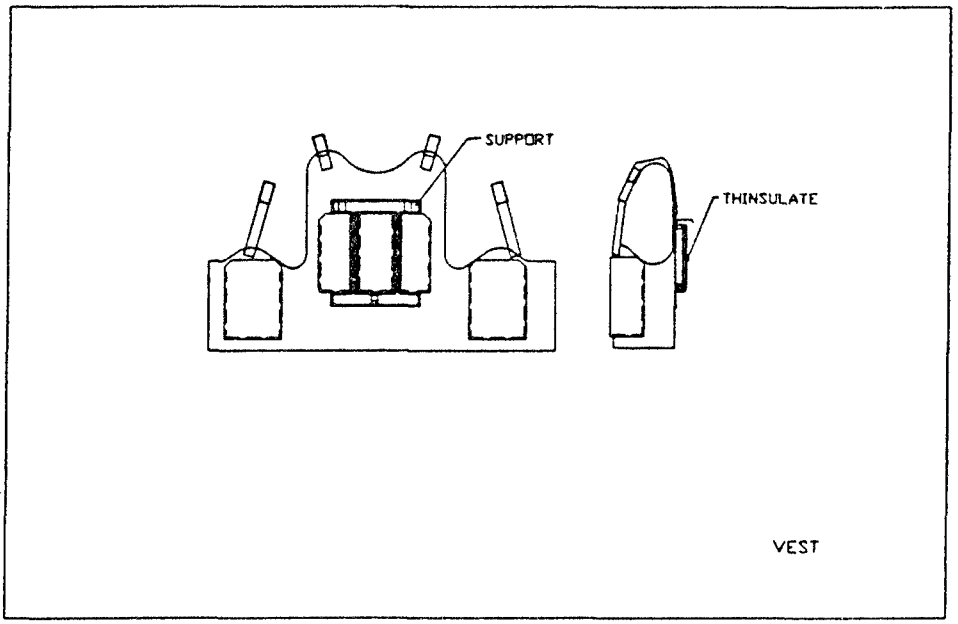


Figure 10. Unwrapped vest

Figure 10 illustrates how the vest can be arranged to accommodate the cylinder assembly. Each group of tubes is placed in a pocket in the vest, which has insulation on the outside. This arrangement limits the cooling lost to the outside.

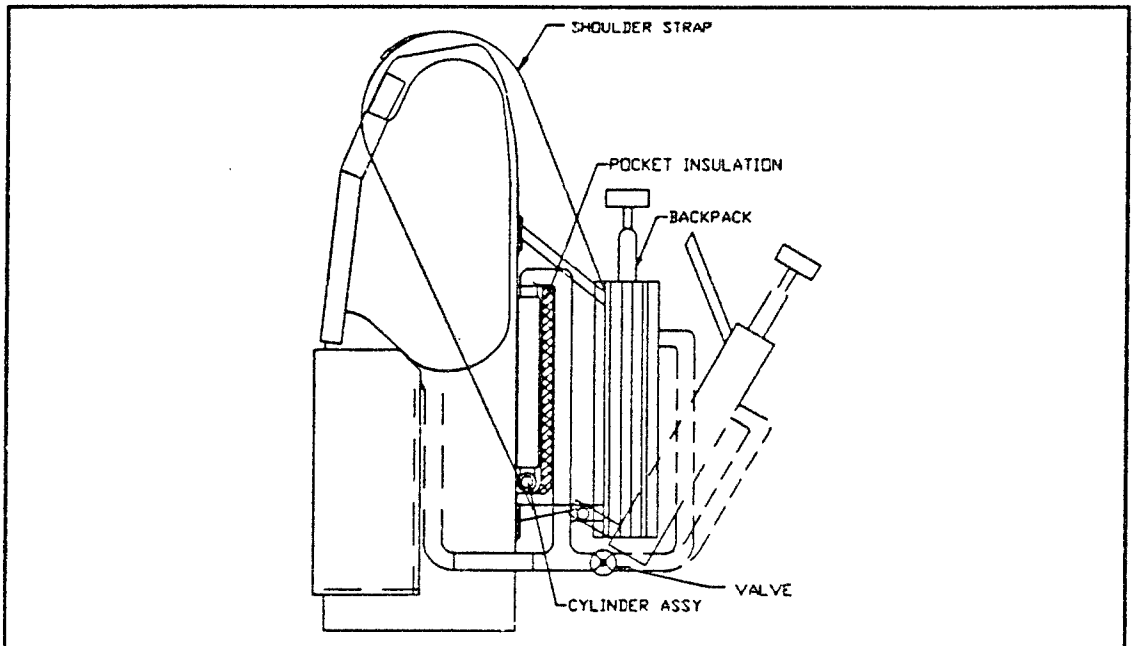


Figure 11. Adsorption backpack and vest assembly

This illustration shows how the backpack is attached to the vest that contains the water evaporator tubes. In one configuration, the backpack is flexed to the rear to permit the wearer to put on a protective jacket. Once the jacket is in place, the backpack can be pulled up in place and the shoulder straps attached. This arrangement gives the wearer easy access to the control valve to adjust the flow of water vapor to backpack and thus regulate the vest temperature. Two changes were made in the design; first, the attachment to the backpack was moved from the bottom to the top of the backpack; and second, flexible tubing was used to connect the backpack to the water reservoir.

TASK 4. Demonstrate the Prototype System

Cooling Rate Measurements

The prototype adsorption system was tested to determine the operating characteristics by measuring the power required to maintain the evaporator temperature at 35 °C. This was accomplished by immersing the evaporator section of the backpack system in a water bath and measuring the power supplied to a heater, also located in the bath, to maintain the 35 °C bath temperature. This experimental design is shown in Figure 12.

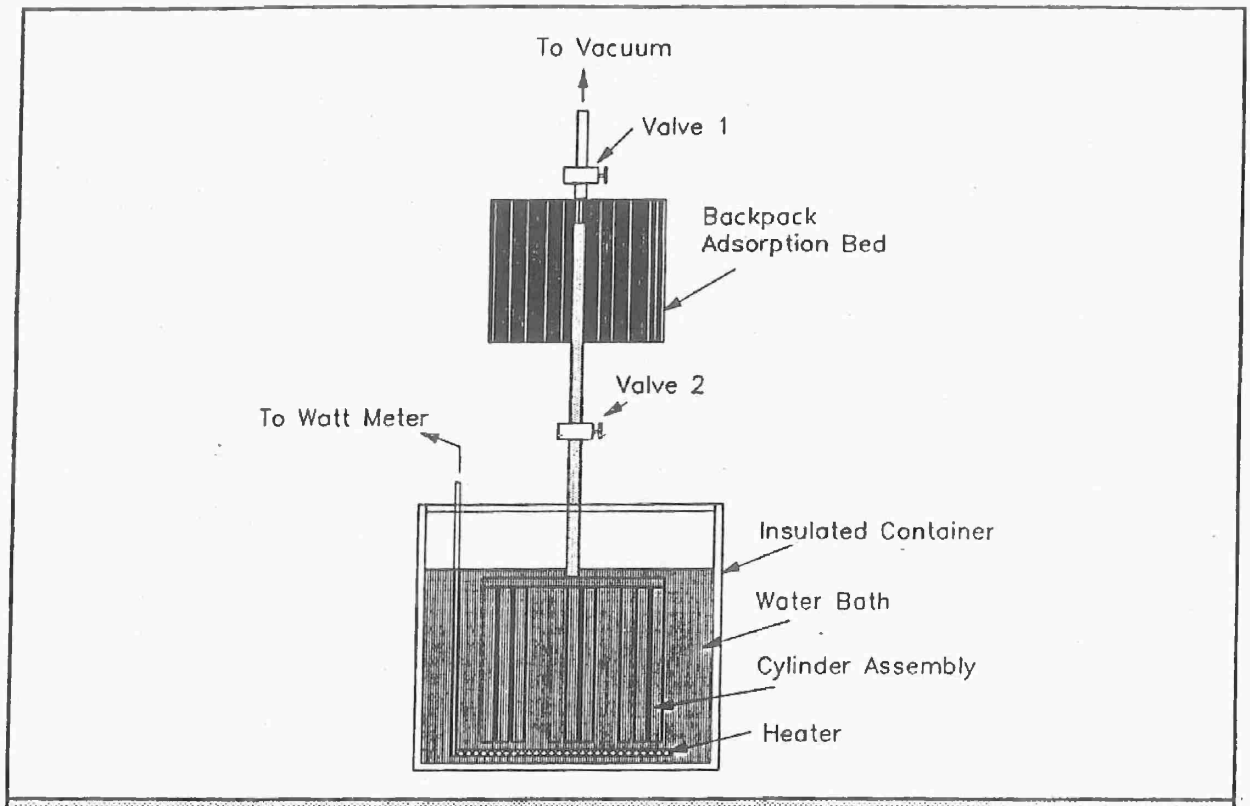


Figure 12. Prototype adsorption system cooling rate testing apparatus

The procedure used in these tests was to degas the water reservoir/evaporator (cylinder assembly) section by first evacuating the adsorption bed and then closing valve 1; next, valve 2 was carefully opened, which allows air to flow to the adsorption bed; then, valve 2 was closed and valve 1 was opened to reevacuate the adsorption bed. This cycle was repeated several times to assure that any dissolved air in the water reservoir/evaporator was removed. The last step to prepare the system for testing was to evacuate the adsorption bed. Typically we evacuated the adsorption bed to 0.15 torr. Testing was started after the adsorption cooling system was prepared.

The testing procedure that was followed for these measurements was to establish the power setting required to maintain the water bath at 35 °C. Then, valve 2, the control valve, was opened and the power setting increased to again maintain the bath temperature at 35 °C. The difference between the two power settings is a measure of the cooling performance of the system.

Experimentally, we had difficulties in removing all of the vacuum leaks from the system. Therefore, we have not measured the maximum output potential of the system. However, we have been able to obtain a maximum cooling rate of 180 W for several min. After

that point, the rate continued to drop, which is an indication of air leaks into the system. Table 5 shows a summary of the cooling capacity data collected.

Table 5. Cooling Capacity of Adsorption Backpack

Run Time min	Max Power W	Bath Temperature °C	Fin Temperature °C
15	137	35	28
30	178	35	26
20	170	35	29

System Specifications

The current characteristics of the backpack adsorption cooling system are listed below in Table 6.

Table 6. Backpack Adsorption Cooling System Specifications

Property	Value
Backpack weight	52 lb
Water reservoir/evaporator weight	12 lb
Vest weight	5 lb
Magnesium chloride	4.9 lb
Molecular sieves	0.7 lb
Water	5.6 lb
Total system weight for 1st prototype	80.2 lb
Cooling rate (design)	325 to 432 W
Cooling capacity	300 W for 6 h

All of the values for the specifications are in a reasonable range with the exception of the backpack and water reservoir, which were anticipated to be high due to the construction materials and the fabrication methods. The vest is somewhat heavier than expected; however, this is due to the metal frame needed to support the backpack.

We have considered other methods of manufacturing the backpack and water reservoir, which would be significantly lighter. For example, the cylinder assembly (water reservoir/evaporator) could be constructed with stainless steel tubing with a 0.012 wall thickness. This would change the weight of the system as indicated below.

1.	Cylinder assembly	3 lb
2.	Backpack	6.1 lb
3.	Vest	3.5 lb
	Total system weight	12.6 lb

These material changes could make a significant difference in the weight of the system. The weight of the required chemicals would be unchanged at 11.2 lb. Therefore, the weight of this system when filled with water and desiccant would be 23.8 lb instead of 80.2 lb.

Changing the design of the backpack materials and method of construction would greatly improve the control over potential system leaks. In addition, we have maintained the same surface area in the new backpack, which would provide similar heat transfer characteristics. This is particularly true since the fins will be shorter in the new design.

An example of a new backpack is illustrated in Figure 13, where we show how thin stainless steel sheet could be formed into fins and the adsorption bed. Consideration was given to the mechanical strength and heat transfer characteristics in developing the new design. The current weight was based on a thickness of sheet stainless steel that would provide a minimum deflection of 0.125 in. for an unsupported wall under 14.7 psi pressure. This thickness could be reduced if the influence of the desiccant in the backpack was considered. The heat transfer for short fins is primarily a function of surface area; therefore, we have used approximately the same area as was used in the brass prototype. The design shown in Figure 13 should be easier to control potential leaks since only two edges need to be sealed.

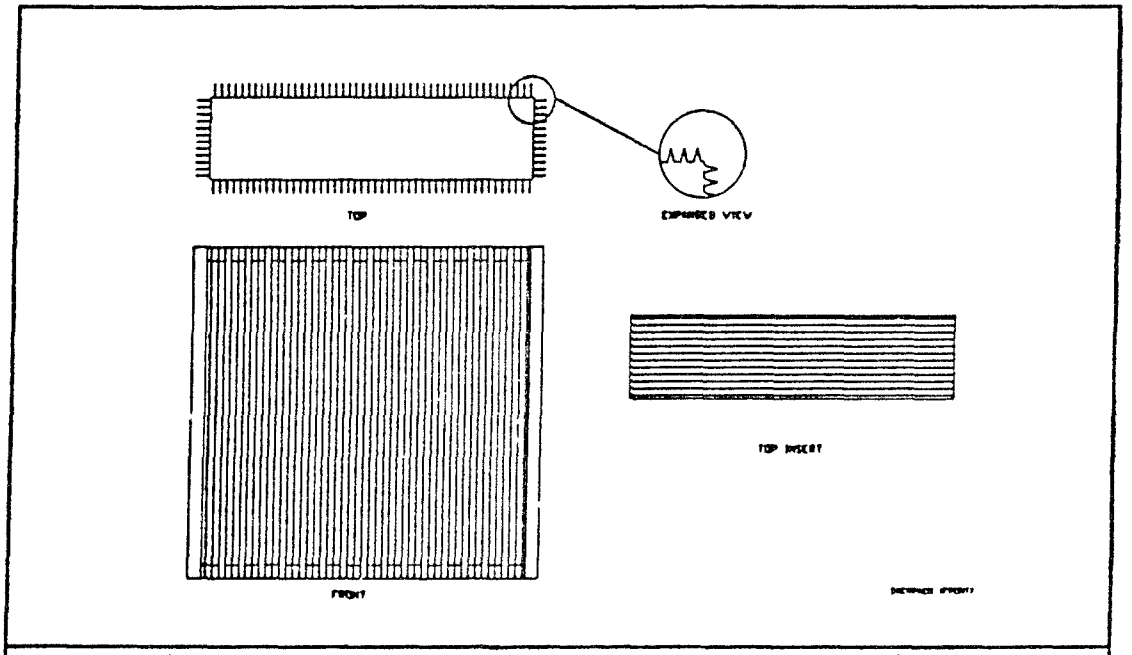


Figure 13. New backpack design

CONCLUSIONS

Based on our current laboratory results, the adsorption cooling concept does provide significant cooling (170 W); however, due to system leaks, the maximum potential has not been reached. There are design difficulties with the current system which are beyond system weight. These problems relate to the system's comfort and ease of use. There is difficulty in handling and wearing the cylinders in the vest and there are potential problems with the vacuum requirements. However, we have recorded good evidence that it would be possible to provide 300 W of cooling for the required time if the system was constructed to minimize the potential for leaks.

APPENDIX A

SYSTEM SAFETY PROGRAM

APPENDIX A

SYSTEM SAFETY PROGRAM

(Final Version)

Design, Manufacture, and Implementation of Individual Soldier Backpack Cooling Systems

1. Purpose

This System Safety Program Plan is a description of the planned methods to be used by Mainstream Engineering Corporation to implement the tailored requirements of MIL-STD-882B for the Design, Manufacture, and Implementation of Individual Soldier Backpack Cooling Systems. The plan includes organizational responsibilities, resources, methods of accomplishment, milestones, depth of effort, and integration with other program engineering and management activities and related systems.

The purpose of this procedure is to make all efforts to identify and reduce those safety hazards pertaining to the backpack and its system components. Mainstream will follow the guidelines set forth by MIL-STD-882B. It will apply to all phases of the life cycle, e.g., research, design, technology development, testing and evaluation, and manufacture of the deliverable.

2. Scope

This procedure will apply to all Mainstream personnel, and will be monitored by the Safety Officer, Dr. Clyde F. Parrish.

3. Reference

MIL-STD-882B Military Specification "System Safety Program Requirements", 30 March 1984.

This reference provides the requirements for developing and implementing a system safety program of sufficient comprehensiveness to identify the hazards of a system and to impose design requirements and management controls to prevent mishaps by eliminating hazards or reducing the associated risk to a level acceptable to the managing activity (MA). The term "managing activity" usually refers to the Government procuring activity, but may include prime or associate contractors or subcontractors who wish to impose system safety tasks on their suppliers.

4. Applicability

This system safety program plan applies to all test, maintenance and support, and training equipment used in this program. It applies to all activities of the system life cycle, e.g., research, design, technology development, test and evaluation, production, construction, operation and support, modification and disposal.

5. System Safety Program Objectives

The system safety program defines a systematic approach to make sure:

a. Safety, consistent with mission requirements, is designed into the backpack system in a timely, cost-effective manner.

b. Hazards associated with each system are identified, evaluated, and eliminated, or the associated risk reduced to a level acceptable to the MA throughout the entire life cycle of a system. Risk shall be described in risk assessment terms.

c. Historical safety data, including lessons learned from other systems, are considered and used.

d. Minimum risk is sought in accepting and using new designs, materials, and production and test techniques.

e. Actions taken to eliminate hazards or reduce risk to a level acceptable to the MA are documented.

f. Retrofit actions required to improve safety are minimized through the timely inclusion of safety features during research and development of the backpack cooling system.

g. Changes in design, configuration, or mission requirements are accomplished in a manner that maintains a risk level acceptable to the MA.

h. Consideration is given to safety, ease of disposal, and demilitarization of any hazardous materials associated with the system.

i. Significant safety data are documented as "lessons learned" and are submitted to MA in the appropriate reports and specifications.

6. System Safety Design Requirements

System safety design requirements will be specified after review of pertinent standards, specifications, regulations, design handbooks and other sources of design guidance for applicability to the design of the system. Some general system safety design requirements are:

a. Eliminate identified hazards or reduce associated risk through design, including material selection or substitution. When potentially hazardous materials must be used, select those with least risk throughout the life cycle of the system.

b. Isolate hazardous substances, components, and operations from other activities, areas, personnel, and incompatible materials.

c. Locate equipment so that access during operations, servicing, maintenance, repair, or adjustment minimizes personnel exposure to hazards (e.g., hazardous chemicals, high voltage, electromagnetic radiation, cutting edges, or sharp points).

d. Minimize risk resulting from excessive environmental conditions (e.g., temperature, pressure, noise, toxicity, acceleration and vibration).

e. Design to minimize risk created by human error in the operation and support of the system.

f. Consider alternate approaches to minimize risk from hazards that cannot be eliminated. Such approaches include interlocks, redundancy, fail-safe design, system protection, fire suppression, and protective clothing, equipment, devices, and procedures.

g. Protect the power sources, controls and critical components of redundant subsystems by physical separation or shielding.

h. When alternate design approaches cannot eliminate the hazard, provide warning and caution notes in assembly, operation, maintenance, and repair instructions, and distinctive markings on hazardous components and materials, equipment, and facilities to ensure personnel and equipment protection. These shall be standardized in accordance with MA requirements.

i. Minimize the severity of personnel injury or damage to equipment in the event of a mishap.

j. Design software controlled or monitored functions to minimize initiation of hazardous events or mishaps.

k. Review design criteria for inadequate or overly restrictive requirements regarding safety. Recommend new design criteria supported by study, analyses, or test data.

7. System Safety Precedence

The order of precedence for satisfying system safety requirements and resolving identified hazards shall be as follows:

a. Design for Minimum Risk. From the first, design to eliminate hazards. If an identified hazard cannot be eliminated, reduce the associated risk to an acceptable level, as defined by the MA, through design selection.

b. Incorporate Safety Devices. If identified hazards cannot be eliminated or their associated risk adequately reduced through design selection, that risk shall be reduced to a level acceptable to the MA through the use of fixed, automatic, or other protective safety design features or devices. Provisions shall be made for periodic functional checks of safety devices when applicable.

c. Provide Warning Devices. When neither design nor safety devices can effectively eliminate identified hazards or adequately reduce associated risk, devices shall be used to detect the condition and to produce an adequate warning signal to alert personnel of the hazard. Warning signals and their application shall be designed to minimize the probability of incorrect personnel reaction to the signals and shall be standardized within like types of systems.

d. Develop Procedures and Training. Where it is impractical to eliminate hazards through design selection or adequately reduce the associated risk with safety and warning devices, procedures and training shall be used. However, without a specific waiver, no warning, caution, or other form of written advisory shall be used as the only risk reduction method for Category I or II hazards (as defined in Table 1). Precautionary notations shall be standardized as specified by the MA. Tasks and activities judged critical by the MA may require certification of personnel proficiency.

8. Risk Assessment

Decisions regarding resolution of identified hazards shall be based on assessment of the risk involved. To aid the achievement of the objectives of system safety, hazards shall be characterized as to hazard severity categories and hazard probability levels, when possible. Since the priority for system safety is eliminating hazards by design, a risk-assessment procedure considering only hazard severity will generally suffice during the early design phase to minimize risk. When hazards are not eliminated during the early design phase, a risk assessment procedure based upon the hazard probability, as well as hazard severity, shall be used to establish priorities for corrective action and resolution of identified hazards.

9. Hazard Severity

Hazard severity categories are defined to provide a qualitative measure of the worst credible mishap resulting from personnel error; environmental conditions; design inadequacies; procedural deficiencies; or system, subsystem or component failure or malfunction and are listed in Table 1. These hazard severity categories provide guidance to a wide variety of programs. However, adaptation to a

particular program is generally required to provide a mutual understanding between the MA and the contractors as to the meaning of the terms used in the category definitions. The adaptation must define what constitutes system loss, major or minor system damage, and severe and minor injury and occupational illness.

Table 1. Hazard Severity Categories

Description	Category	Mishap Definition
Catastrophic	I	Death or system loss.
Critical	II	Severe injury, severe occupational illness, or minor system damage.
Marginal	III	Less than minor injury, occupational illness, or minor system damage.
Negligible	IV	Less than minor injury, occupational illness, or system damage.

For the proposed backpack design, catastrophic failure can be defined as the inability of the unit to provide any cooling to the user. Malfunction of the backpack and subsequent failure of the system would be classified as a category III or marginal result. It is anticipated that failure could, at worst, result in insufficient cooling (i.e., heat removal) which could be consequently followed by heat-related illness.

10. Hazard Probability

The probability that a hazard will be created during the planned life expectancy of the system can be described in potential occurrences per unit of time, events, population, items, or activity. Assigning a quantitative hazard probability to a potential design or procedural hazard is generally not possible early in the design process. A qualitative hazard probability may be derived from research, analysis and evaluation of historical safety data from similar systems. Supporting rationale for assigning a hazard probability shall be documented in hazard analysis reports. An example of a qualitative hazard probability ranking is presented in MIL-STD-882B.

The probability of a hazard being created during the life expectancy of the backpack unit could be classified as remote, providing the routine maintenance is performed at the required intervals, the unit has not been subjected to abnormal or willful abuse, and has not been modified in any way.

11. Action on Identified Hazards

Action shall be taken to eliminate identified hazards or reduce the associated risk. CATASTROPHIC and CRITICAL hazards shall be eliminated or their associated risk reduced to a level acceptable to the MA. If this is impossible or impractical, alternatives shall be recommended to the MA.

12. Use of Existing Technology

Test data and performance specifications are already known on the majority of these components, making these items of minimal risk. Mainstream is still in the process of evaluating the design of these items and their expected performance in the system. These system components are also being evaluated as to their safety factor and the probability of failure when operated in a hostile military environment. Any component that Mainstream sees as compromising the performance and safety objectives will be reevaluated and, if necessary, respecified or redesigned.

13. Safety During Manufacturing

Protective measures that are routinely taken by the company are the wearing of protective gloves and the donning of protective overalls and respirators. Exhaust ventilators are also installed to remove fumes and dust. The entire facility is air-conditioned to provide a clean and comfortable working environment.

14. Workmanship and Quality Control

All workmanship and quality control will meet or exceed all requirements of the military specifications. Assembly of the backpacks will be under strict supervision and conducted in the clean-room here at Mainstream Engineering. Prototype backpacks will be tested and qualified to military specifications prior to shipping in approved containers to Natick.

15. Personnel Injury

Design and manufacture of the backpacks will be such that the housing can be handled without wearing gloves or special equipment. Corners will be rounded, catches and locks will be recessed, shoulder straps will be padded and adjustable, and the weight will be within the objectives set by the contract. The exterior of the housing will be sealed and protected, and will present no health problems to personnel either while being worn or when stored in quantity.

16. Foolproofing

Design of the backpack will be such that minimal skill and minimal prior training will be required for successful operation. Controls will be well-defined and clearly labeled, and connectors will be unique to prevent mismatched connections.

17. Personnel Protection

All efforts will be made to design, build and label the backpack to protect the user from:

a. Injury resulting from catastrophic failure of any single component or combination of components within the enclosure.

b. Fuel leaks resulting from a ruptured fuel line, inverted backpack, or other inadvertent, unpredictable event.

c. Burns resulting from hot exhaust gas, hot engine/compressor components and hot condenser surface temperatures.

d. Injury resulting from extended wear of the unit. That is, it shall be ergonomically designed to be comfortably worn by the 5th percentile female through the 95th percentile male.

e. Leaks resulting from the failure of the refrigerant lines, compressor or related components.

f. Injury resulting from confusion over operation, maintenance and refueling while in the field.

g. Fatigue resulting from field operations.

h. Field detection by visible means.

i. Injury or toxic fume poisoning resulting from emitted exhaust gas. Exhaust gas will be directly away from the user.

18. Electromagnetic Interference (EMI)/Radiofrequency Interference (RFI) Shielding

All efforts will be made to reduce EMI/RFI radiation from the backpack that could give away a user's location in the field. Techniques such as foil coating on inside surfaces or impregnation of the composite structure with metal fibers will be used. EMI/RFI radiation performance will be measured and documented from the prototype and submitted for Natick's evaluation.

19. Chemical Absorption

The composite materials of the backpack shall be selected to be inert to decontaminating solutions such as DS2, C8, or ICBAD. The housing will be designed to be impervious and therefore retention-free, of these solutions and therefore will present no health problems to the user. Compliance with the chemical absorption standards shall be conducted at Mainstream Engineering.

20. Infrared Radiation

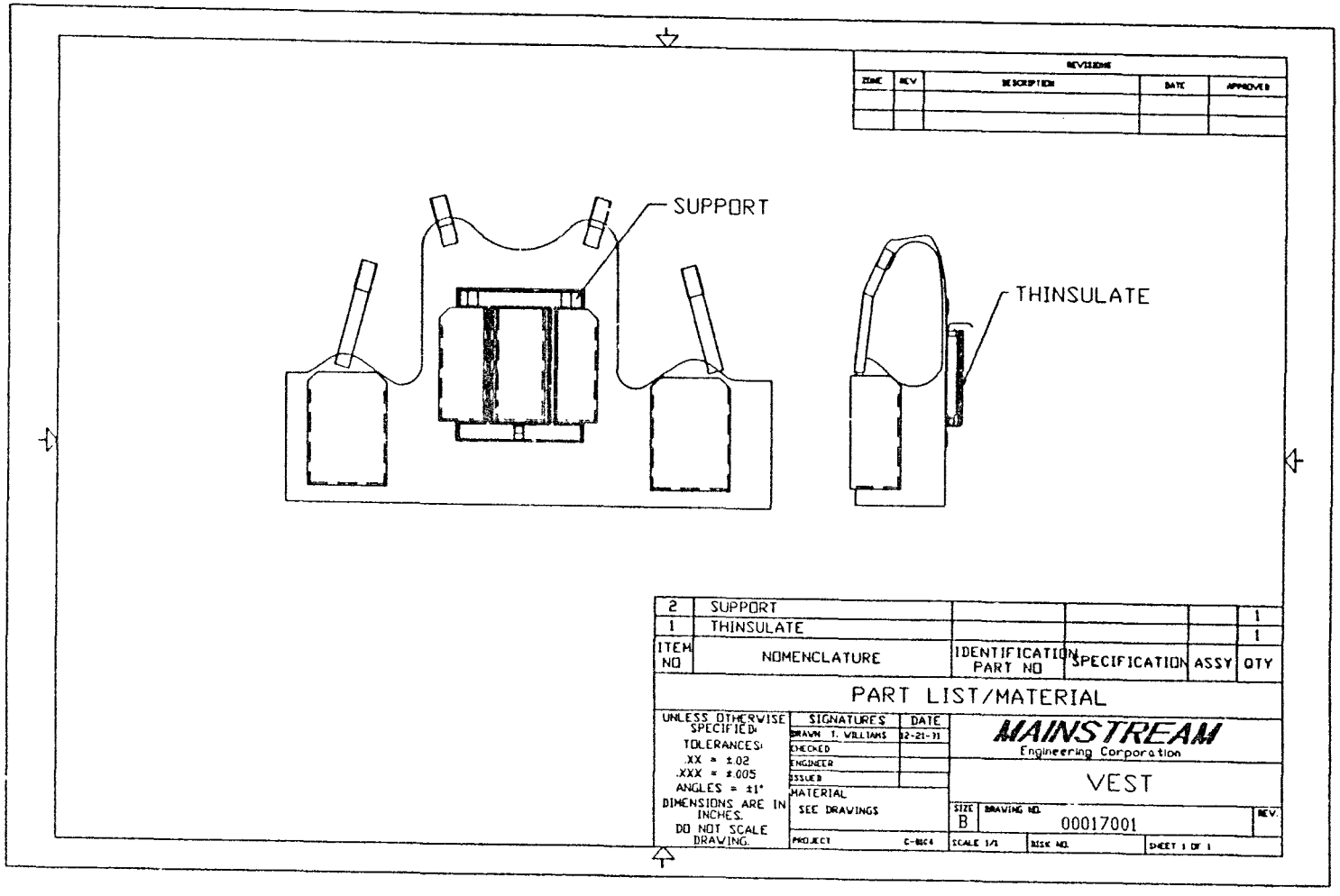
Every attempt will be made to reduce infrared emission in accordance with MIL-C-46168 and MIL-C-53039. Surfaces will be coated or impregnated to achieve this objective.

21. Review Meetings

During Mainstream's review meetings, any changes or deviations to the system safety program will be voiced and documented. These results will be communicated to the MA. Dr. Clyde Parrish is responsible for component and system safety at Mainstream Engineering. The address is Mainstream Engineering, 200 Yellow Place, Rockledge, FL 32955, and the phone number is (407) 631-3550.

APPENDIX B

CONSTRUCTION DRAWINGS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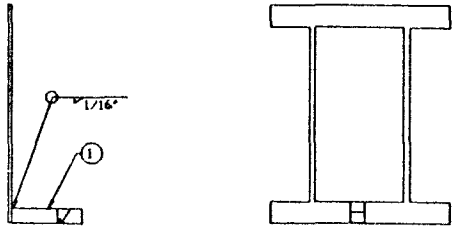
REV
SCALE 1/1
BISK NO.
SHEET 1 OF 1

NOTES

1. TO BE MADE OF 1/16" THICK SHEET METAL.

REVISIONS				
ZONE	REV	DESCRIPTION	DATE	APPROVED
	A	REVISED AND REDRAWN	2-4-92	



TYP.

ITEM NO	NOMENCLATURE	IDENTIFICATION PART NO	SPECIFICATION	ASSY	QTY
1	SUPPORT-VEST	00017006			1

PART LIST/MATERIAL

UNLESS OTHERWISE SPECIFIED:
TOLERANCES:
.XX = ±.02
.XXX = ±.005
ANGLES = ±1°
DIMENSIONS ARE IN INCHES.
DO NOT SCALE DRAWING.

SIGNATURES	DATE
DRAWN T. WILLIAMS	12-21-91
CHECKED	
ENGINEER	
ISSUED	

MATERIAL: STAINLESS STEEL

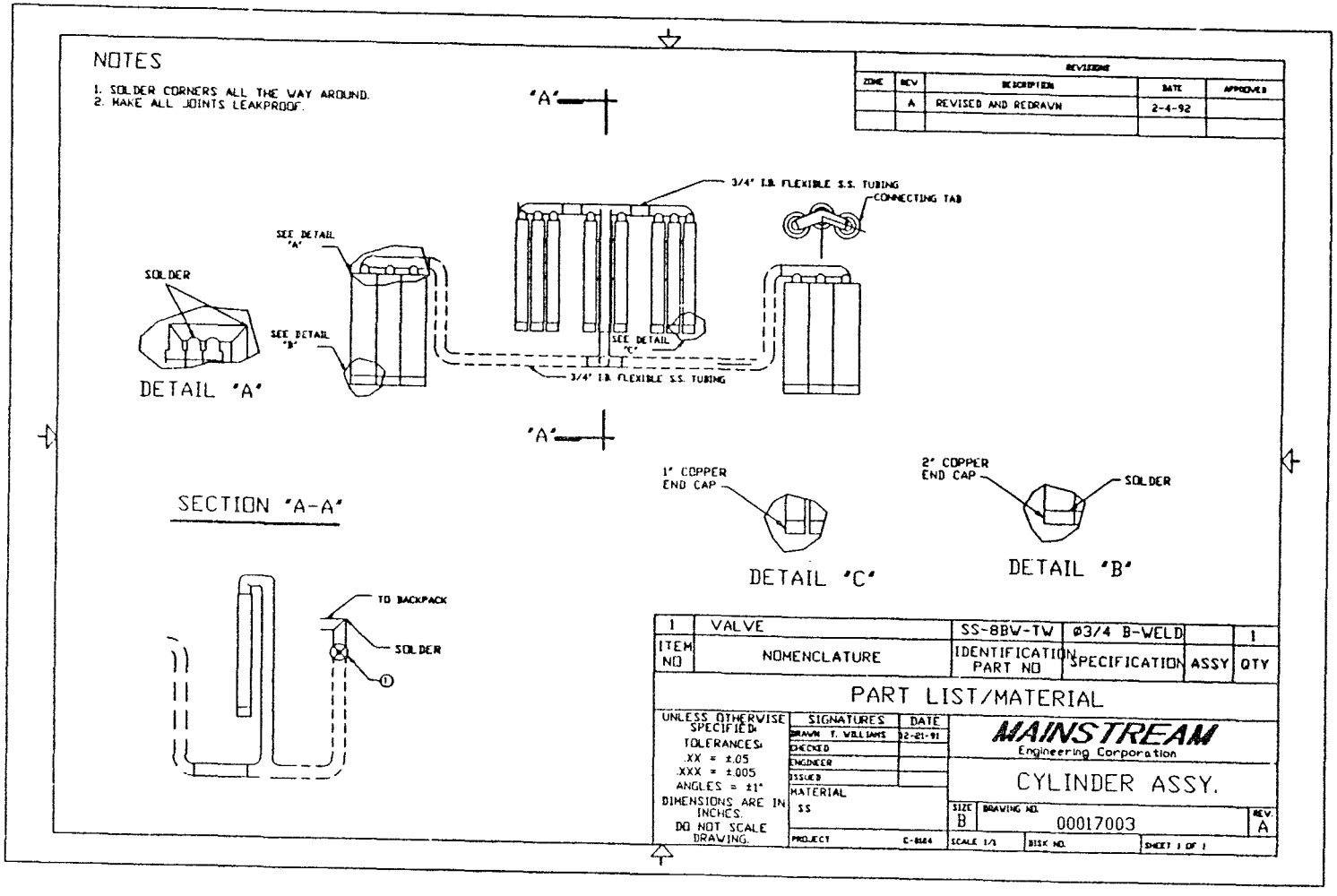
PROJECT C-0684

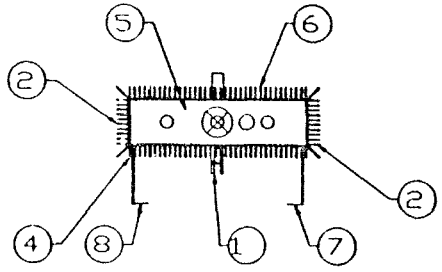
MAINSTREAM
Engineering Corporation

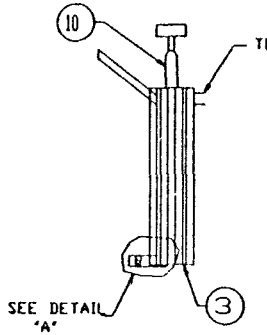
SUPPORT

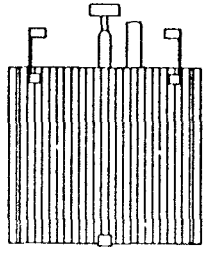
SIZE B | DRAWING NO. 00017002 | REV. A

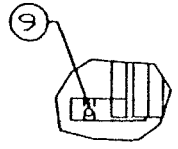
SCALE 1/1 | DISK NO. | SHEET 1 OF 1


NOTES
1. SOLDER CORNERS ALL THE WAY AROUND.
2. MAKE ALL JOINTS LEAKPROOF.
'A'
REVISIONS
ZONE | REV | DESCRIPTION | DATE | APPROVED
A | REVISED AND REDRAWN | 2-4-92
3/4" I.D. FLEXIBLE S.S. TUBING
CONNECTING TAB
SEE DETAIL 'A'
SEE DETAIL 'B'
SEE DETAIL 'C'
SOLDER
3/4" I.D. FLEXIBLE S.S. TUBING
DETAIL 'A'
'A'
SECTION 'A-A'
TO BACKPACK
SOLDER
1" COPPER END CAP
DETAIL 'C'
2" COPPER END CAP
SOLDER
DETAIL 'B'
1 | VALVE | SS-8BV-TW | ø3/4 B-WELD | | 1
ITEM NO | NOMENCLATURE | IDENTIFICATION PART NO | SPECIFICATION | ASSY | QTY
PART LIST/MATERIAL
UNLESS OTHERVISE SPECIFIED
TOLERANCES:
.XX = ±.05
.XXX = ±.005
ANGLES = ±1°
DIMENSIONS ARE IN INCHES
DO NOT SCALE DRAWING.
SIGNATURES | DATE
DRAWN T. WILLIAMS | 12-21-91
CHECKED
ENGINEER
ISSUED
MATERIAL
SS
PROJECT E-8684
MAINSTREAM
Engineering Corporation
CYLINDER ASSY.
SIZE B | DRAWING NO. 00017003 | REV A
SCALE 1/1 | DISK NO. | SHEET 1 OF 1









DETAIL "A"

REVISIONS				
ZONE	REV	DESCRIPTION	DATE	APPROVED
	A	REVISED AND REDRAWN	2-4-92	

ITEM NO	NOMENCLATURE	IDENTIFICATION PART NO	SPECIFICATION	ASSY	QTY
10	RECHARGE VALVE	SS-6BW-TW	Ø1/2 B-WELD		1
9	DOWEL PIN 5/16"	J-DWX-5-8			1
8	BRACE-LEFT	00017015			1
7	BRACE-RIGHT	00017014			1
6	BACKPACK-BACK	00017013			1
5	BACKPACK-TOP	00017012			1
4	BACKPACK-FRONT	00017011			1
3	BACKPACK-BOTTOM	00017010			1
2	BACKPACK-SIDES	00017009			2
1	SUPPORT-BACKPACK	00017005			1

PART LIST/MATERIAL

UNLESS OTHERWISE SPECIFIED:
TOLERANCES:
.XX = ±.02
.XXX = ±.005
ANGLES = ±1°
DIMENSIONS ARE IN INCHES.
DO NOT SCALE DRAWING

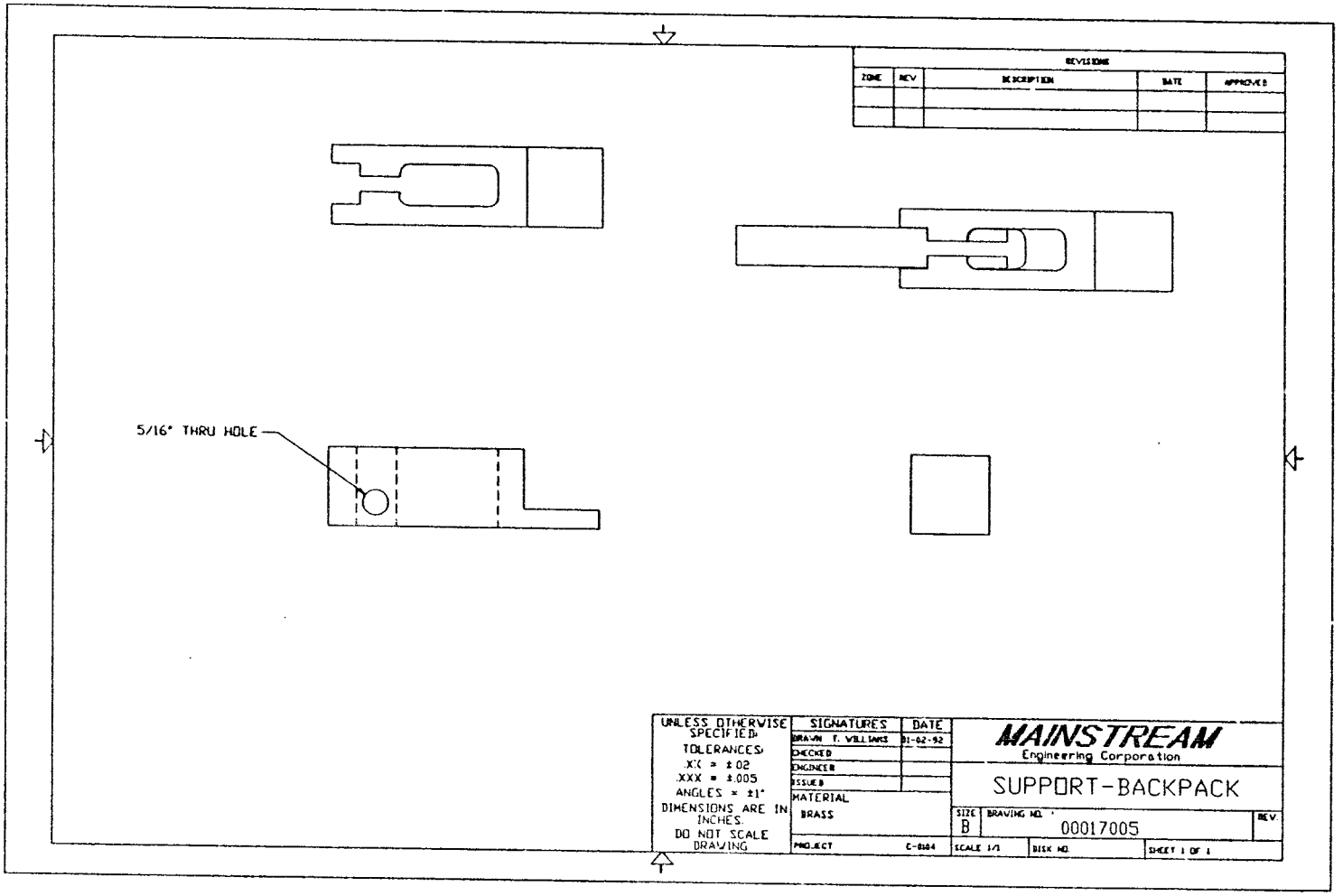
SIGNATURES	DATE
DRAWN T. WILLIAMS	12-21-91
CHECKED	
ENGINEER	
ISSUED	
MATERIAL: SEE DRAWINGS	
PROJECT C-6684	

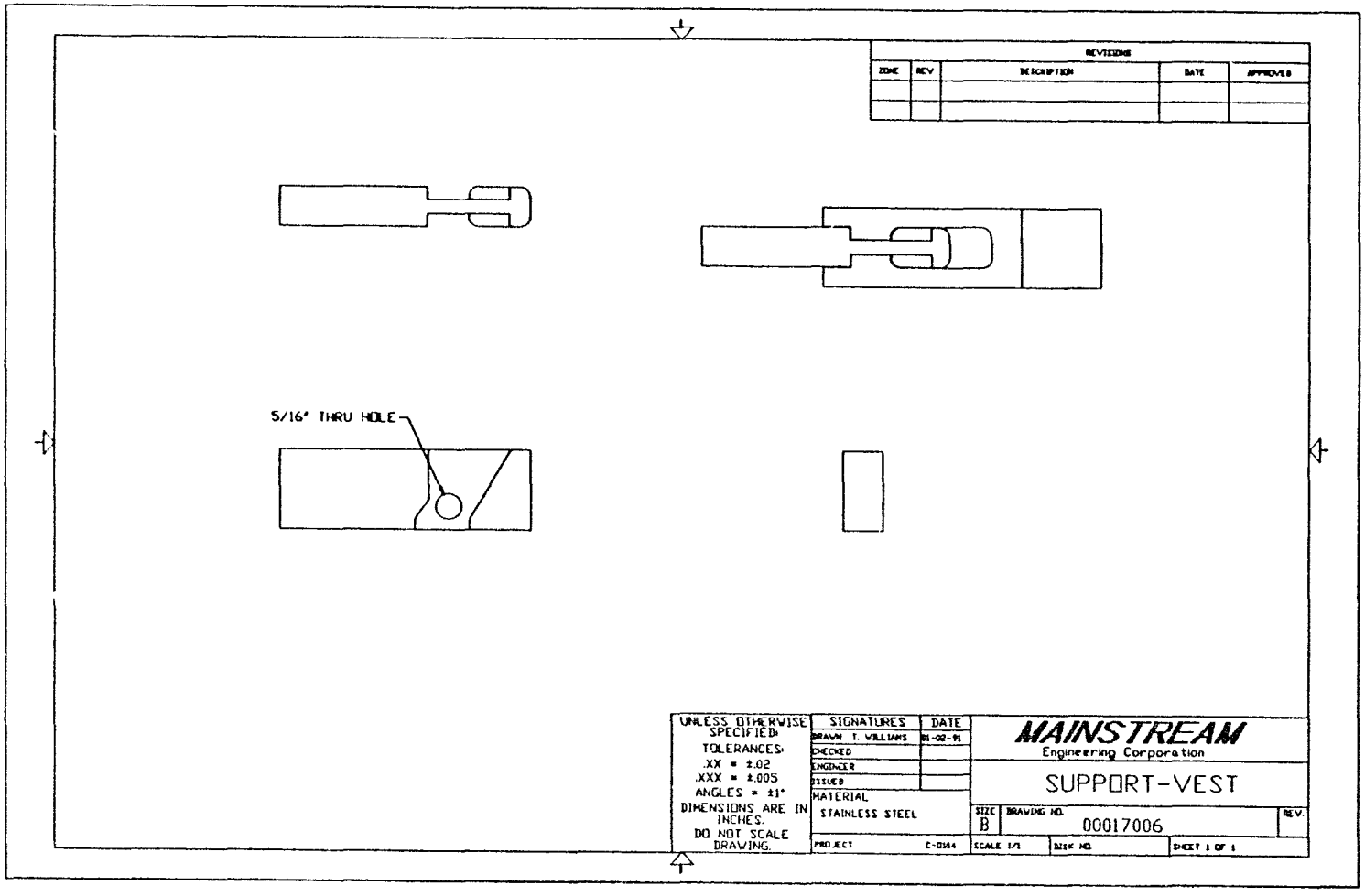
MAINSTREAM
Engineering Corporation

BACKPACK ASSY.

SIZE	DRAWING NO.	REV.
B	00017004	A

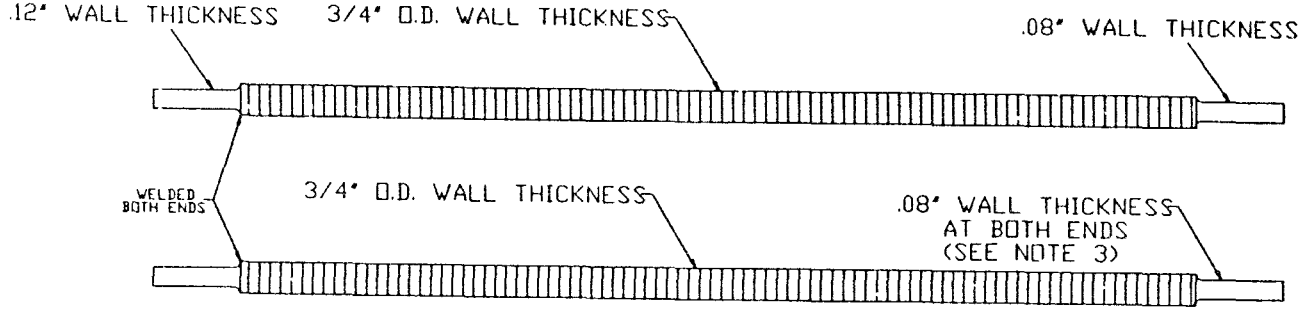
SCALE 1/1 | DISK NO. | SHEET 1 OF 1


REVISIONS
ZONE
REV
DESCRIPTION
DATE
APPROVED
5/16" THRU HOLE
UNLESS OTHERWISE SPECIFIED:
TOLERANCES:
.XX = ±.02
.XXX = ±.005
ANGLES = ±1°
DIMENSIONS ARE IN INCHES.
DO NOT SCALE DRAWING
SIGNATURES
DATE
DRAWN T. WILLIAMS 01-02-92
CHECKED
ENGINEER
ISSUED
MATERIAL
BRASS
PROJECT C-8184
MAINSTREAM
Engineering Corporation
SUPPORT-BACKPACK
SIZE B
DRAWING NO. 00017005
REV
SCALE 1/1
DISK NO.
SHEET 1 OF 1


REVISIONS
ZONE
REV
DESCRIPTION
DATE
APPROVED
5/16" THRU HOLE
UNLESS OTHERWISE SPECIFIED:
TOLERANCES:
.XX = ±.02
.XXX = ±.005
ANGLES = ±1°
DIMENSIONS ARE IN INCHES.
DO NOT SCALE DRAWING.
SIGNATURES
DATE
DRAWN T. WILLIAMS
01-02-91
CHECKED
ENGINEER
ISSUED
MATERIAL
STAINLESS STEEL
PROJECT
C-0144
MAINSTREAM
Engineering Corporation
SUPPORT-VEST
SIZE
B
DRAWING NO.
00017006
REV.
SCALE 1/1
DISK NO.
SHEET 1 OF 1

NOTES
1. DIMENSIONS ARE THE SAME ON ALL ASSEMBLIES.
2. MAKE ALL JOINTS LEAKPROOF.
3. THERE ARE TWO ASSY. TO BE MADE OF THE .06" TUBING.

REVISIONS				
ZONE	REV	DESCRIPTION	DATE	APPROVED
	A	REVISED AND RED[illegible]N	2-4-92	



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	DRAWN T. WILLIAMS	1-3-95
	CHECKED	
	ENGINEER	
	ISSUED	
	MATERIAL: STAINLESS STEEL	
	PROJECT C-0184	

MAINSTREAM Engineering Corporation

TUBING-VEST

SIZE	DRAWING NO.	REV.
B	00017007	A

SCALE 2/1 | DISK NO. | SHEET 1 OF 1

NOTES
1. DIMENSIONS ARE THE SAME ON ALL ASSEMBLIES.
2. MAKE ALL JOINTS LEAKPROOF.

REVISIONS				
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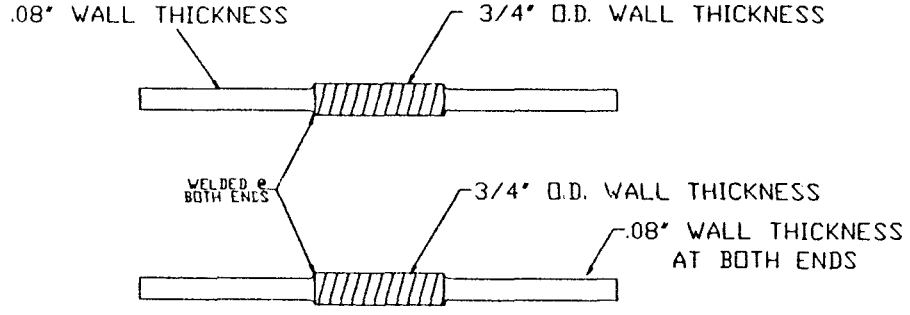

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	DRAWN T. WILLIAMS	1-3-91
	CHECKED	
	ENGINEER	
	ISSUED	
	MATERIAL: STAINLESS STEEL	
	PROJECT C-0184	

MAINSTREAM
Engineering Corporation

TUBING-CYLINDER

SIZE	DRAWING NO.	REV.
B	00017008	A

SCALE 1/1	DISK NO.	SHEET 1 OF 1

NOTES

1. THERE ARE TWO PANELS TO BE MADE WITH THESE DIMENSIONS

REVISIONS				
ZONE	REV	DESCRIPTION	DATE	APPROVED
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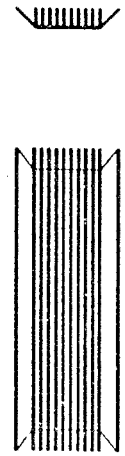

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	CHECKED	
	ENGINEER	
	ISSUED	
	MATERIAL: BRASS	
	PROJECT: C-8684	

MAINSTREAM
Engineering Corporation

BACKPACK-SIDES

SIZE	DRAWING NO.	REV.
B	00017009	A

SCALE 1/4	DESK NO.	SHEET 1 OF 1

NOTES

1. PLEASE CUT THE HOLES BEFORE CUTTING THE FINS.

REVISIONS				
ZONE	REV	DESCRIPTION	DATE	APPROVED
	A	REVISED AND REDRAWN	2-4-92	

UNLESS OTHERWISE SPECIFIED:	SIGNATURES	DATE
TOLERANCES:	DRAWN T. WILLIAMS	1-14-92
.XX = ±.02	CHECKED	
.XXX = ±.005	ENGINEER	
ANGLES = ±1°	ISSUED	
DIMENSIONS ARE IN INCHES.	MATERIAL: BRASS	
DO NOT SCALE DRAWING	PROJECT C-1464	

MAINSTREAM
Engineering Corporation

BACKPACK-BOTTOM

SIZE	DRAWING NO.	REV.
B	00017010	A

SCALE 1/4 | DISK NO. | SHEET 1 OF 1

NOTES

1. THERE WILL BE ONE PANEL MADE WITH THESE DIMENSIONS.

REVISIONS				
ZONE	REV	DESCRIPTION	DATE	APPROVED
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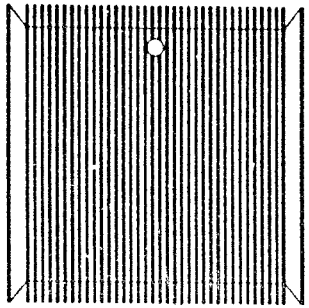


UNLESS OTHERWISE SPECIFIED: TOLERANCES: .XX = ±.02 .XXX = ±.005 ANGLES = ±1° DIMENSIONS ARE IN INCHES. DO NOT SCALE DRAWING.	SIGNATURES	DATE
	DRAWN T. WILLIAMS	1-14-92
	CHECKED	
	ENGINEER	
	ISSUED	
	MATERIAL: BRASS	
	PROJECT C-0004	

MAINSTREAM
Engineering Corporation

BACKPACK-FRONT

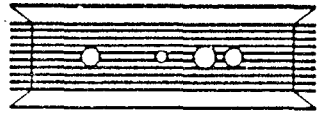
SIZE	DRAWING NO.	REV.
B	00017011	A

SCALE 1/4 | DISK NO. | SHEET 1 OF 1

NOTES

1. PLEASE CUT THE HOLES BEFORE CUTTING THE FINS.

REVISIONS				
ZONE	REV	DESCRIPTION	DATE	APPROVED
	A	REVISED AND REDRAWN	2-4-92	



2 HOLES EQUALLY SPACED

UNLESS OTHERWISE SPECIFIED:	SIGNATURES	DATE
TOLERANCES:	DRAWN F. WILLIAMS	1-14-92
.XX = ±.02	CHECKED	
.XXX = ±.005	ENGINEER	
ANGLES = ±1°	ISSUED	
DIMENSIONS ARE IN INCHES.	MATERIAL: BRASS	
DO NOT SCALE DRAWING	PROJECT C-8164	

MAINSTREAM
Engineering Corporation

BACKPACK-TOP

SIZE	DRAWING NO.	REV.
B	00017012	A

SCALE 1/4 | MIX NO. | SHEET 1 OF 1

NOTES

1. THERE WILL BE ONE PANEL MADE WITH THESE DIMENSIONS.

REVISIONS				
ZONE	REV	DESCRIPTION	DATE	APPROVED
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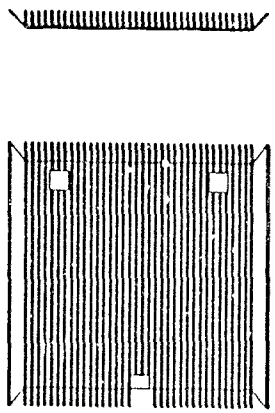

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	CHECKED	
	ENGINEER	
	ISSUED	
	MATERIAL: BRASS	
	PROJECT C-1884	

MAINSTREAM
Engineering Corporation

BACKPACK-BACK

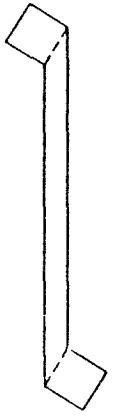
SIZE	DRAWING NO.	REV
B	00017013	A

SCALE 1/4 | DISK NO. | SHEET 1 OF 1

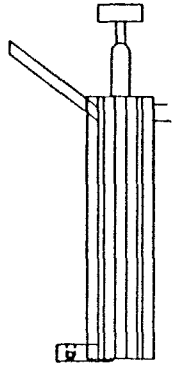
NOTES

1. TO BE MADE OUT OF .125 THICK STOCK.

REVISIONS				
ZONE	REV	DESCRIPTION	DATE	APPROVED



TYP.



SCALE 4/1

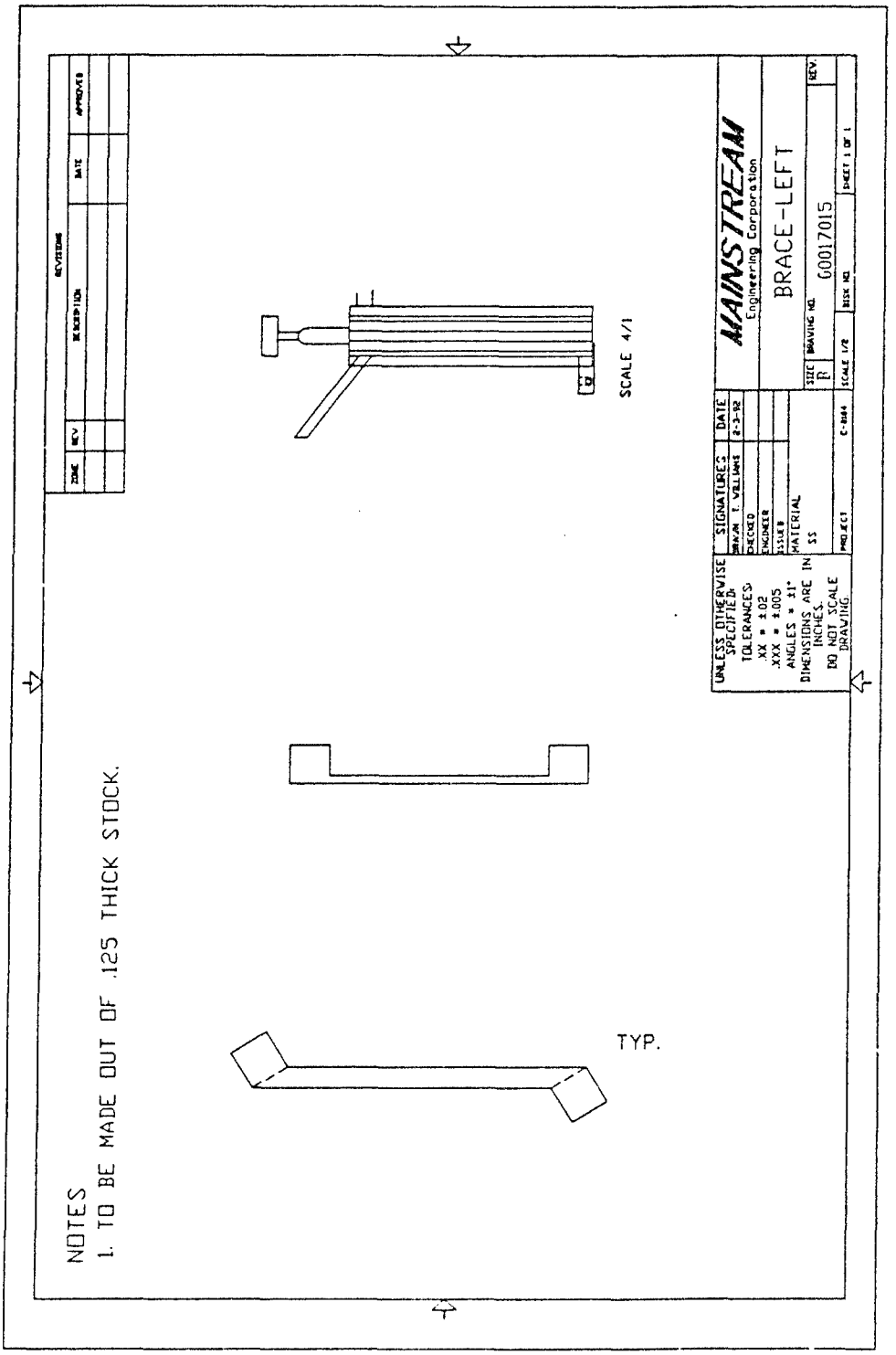
UNLESS OTHERWISE SPECIFIED: TOLERANCES: .XX = ±.02 .XXX = ±.005 ANGLES = ±1° DIMENSIONS ARE IN INCHES. DO NOT SCALE DRAWING	SIGNATURES	DATE
	DRAWN T. WILLIAMS	2-3-92
	CHECKED	
	ENGINEER	
	ISSUED	
	MATERIAL: SS	
	PROJECT C-8884	

MAINSTREAM
Engineering Corporation

BRACE-RIGHT

SIZE	DRAWING NO.	REV.
B	00017014	

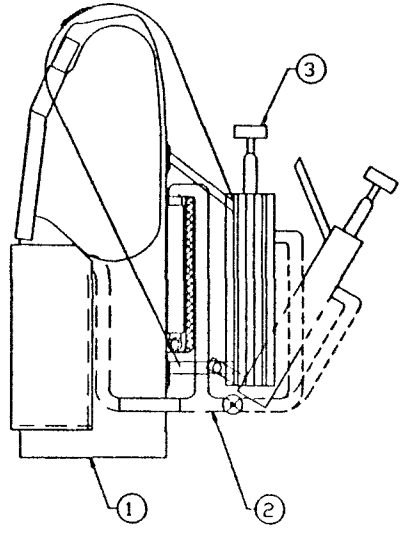
SCALE 1/2 | BOOK NO. | SHEET 1 OF 1


NOTES
1. TO BE MADE OUT OF .125 THICK STOCK.
SCALE 4/1
TYP.
MAINSTREAM
Engineering Corporation
BRACE-LEFT
60017015
UNLESS OTHERWISE SPECIFIED
TOLERANCES
.XX = ±.02
.XXX = ±.005
ANGLES = ±1°
DIMENSIONS ARE IN INCHES.
DO NOT SCALE DRAWING
SIGNATURES
DRAWN T. WILLIAMS
CHECKED
ENGINEER
ISSUED
MATERIAL
SS
DATE
2-3-92
SIZE B
SCALE 1/2
SHEET 1 OF 1
REVISIONS
ZONE
REV
DESCRIPTION
DATE
APPROVED

NOTES

1. VEST
2. CYLINDER ASSY.
3. BACKPACK ASSY.

REVISIONS				
ZONE	REV	DESCRIPTION	DATE	APPROVED



UNLESS OTHERWISE SPECIFIED:	SIGNATURES	DATE
TOLERANCES:	DRAWN T. Williams	3-11-92
.XX = ±.02	CHECKED	
.XXX = ±.005	ENGINEER	
ANGLES = ±1°	ISSUED	
DIMENSIONS ARE IN INCHES.	MATERIAL: SEE DRAWINGS	
DO NOT SCALE DRAWING.	PROJECT: C-884	

MAINSTREAM
Engineering Corporation

BACKPACK ASSY.

SIZE	DRAWING NO.	REV.
B	00017016	

SCALE NTS	DISK NO.	SHEET 1 OF 1

APPENDIX C

SYSTEM SAFETY HAZARD ANALYSIS REPORT

Appendix C

SYSTEM SAFETY HAZARD ANALYSIS REPORT

INTRODUCTION

A System Safety Program was developed (see Appendix A) which described Mainstream's safety program which would be implemented during the design and construction of microclimate cooling devices as part of a Phase II production effort. The Phase I effort was intended to provide a proof-of-concept design, construction of the preliminary prototype system, size and performance data, and a revision of the design for a Phase II effort. It was ultimately determined that this proposed design was not practical from a wearer's perspective since the heat exchange tubes in the vest were too bulky. Therefore, the construction of an adsorption microclimate of this configuration would not proceed to a Phase II effort. However, there have been lessons learned through the course of the development and testing of this microclimate device cooling device that could apply generally to adsorption microclimate cooling systems. This information is provided below as part of the System Hazardous Analysis Report.

The safety criteria was not specifically provided by the contract but was to be tailored to the preliminary prototype development program. Since the testing was done only at the laboratory bench level, no hazardous failures were observed. However, the performance of the microclimate cooling device was below the design level due to vacuum leaks that could not be repaired. This level of performance according to the hazard severity categories (Appendix A, Table 1) would be classified as marginal (category III). If an alternate design, as proposed, were to be used, the vacuum leaks could be controlled. Then the testing could be followed for a sufficiently long period of time to access the life cycles of the components under normal operations or the effects of human errors. However, the use of heat exchangers in the vest and the associated tubing is not a practical design for the wearer.

The outline for the Safety Hazardous Analysis Report follows the description as provided by DI-SAFT-80101, section 7.2 for MIL-STD-882B, Task 204.

SYSTEM DESCRIPTION

There are three major components of the adsorption microclimate cooling system, which are a backpack adsorption bed, an evaporator/cylinder assembly, and a vest to support the backpack and evaporator/cylinder assembly. The adsorption bed and the cylinder assembly are maintained under vacuum (system pressure without water vapor is 10^{-2} torr). Flexible stainless steel tubes are used to connect the cylinder assembly to the backpack. A valve that is between the cylinder assembly and the backpack is used to regulate the flow of water vapor from the evaporator (cylinder assembly) to the backpack (adsorption bed). The system cools the wearer by

absorbing heat from the body with the evaporator which produces water vapor that is transported to the adsorption bed. The water vapor reacts with the desiccant and liberates heat (part of which came from the wearer) to the surroundings. Thus heat is transported from the wearer to the surroundings. Heating the adsorption bed can reverse this process by desorbing the water vapor from the bed and condensing it in the cylinder assembly. The wearer would remove the cooling system for the regeneration step.

The system was designed to provide 300 W of cooling for 6 hr. The heat generated at the adsorption bed is transferred to the surroundings from the surface of the backpack. The backpack surface is finned to promote more effective heat transfer to the surroundings and to prevent a person from touching the hot surface of the backpack. The fin tip temperature was designed to be less than 120 °F (49 °C). Water was selected as the working fluid because of its low toxicity and high latent heat of vaporization. Magnesium chloride was selected as the desiccant, since the weight of water it can adsorb exceeds its weight.

The recharging system consists of two 500 W heaters, each connected through upper temperature limit switches. This prevents the adsorption bed from overheating during the recharging cycle.

The adsorption microclimate cooling system has been described in detail in previous sections of this report and the construction drawings are provided in Appendix B.

DATA

The adsorption microclimate cooling system was tested in the laboratory to determine its cooling capacity and the surface temperature of the backpack fin tips. Our data showed that the tip fin temperature never exceeded 29 °C for a cooling rate of 170 W. Only laboratory testing was done on this preliminary prototype, and this testing was short due to the vacuum problems. We experienced no system failures outside the problems with the vacuum leaks.

HAZARDOUS ANALYSIS RESULTS

Summary of Results

The observations made during the laboratory testing showed that the surface temperature was well below the design upper limit of 49 °C when the cooling exceeded 50% of the design limit. The backpack/cylinder assembly was sealed to be vacuum-tight. One design change that should be made to future backpack systems is the installation of a pressure pop-off valve to prevent over-pressuring the system during recharging.

Identified Hazards

Subsystem Failure Mode(s) - There were no failures of the system outside the design problems associated with the vacuum leaks.

System Event(s) Phase - There were no failures during any of the phases with the exception of the vacuum failure, which was a design flaw.

Effects on System - There were no observed failures of the system; however, the backpack could rupture during recharging if the bed were to overheat.

Risk Assessment - There were no failures of the system during recharging; however, without a pressure control system, the potential exists for failure of the system during recharging. This could happen if the cylinder assembly were not cooled during the recharging cycle. Catastrophic failure of the backpack would be classed as category I; however, the probability of failure would depend on the structural properties of the materials of construction.

Recommended Action - Install a pressure relief valve on the backpack and a high pressure switch in the heater circuit.

Effects of Recommended Action - The effects of these recommended changes would be small and would greatly reduce the risk associated with recharging.

Remarks - Due to other factors such as the bulkiness of the cylinder assembly and the awkwardness of the vacuum piping, this design would not be practical even when the system leaks were removed. Therefore, additional characterization of the safety hazards associated with this microclimate cooling device would not be needed, since the design is impractical.

Status - The status for implementation of the recommendations are low for the changes identified above, since the project is terminated.